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"Agent-Based Simulation and Analysis of Human Behavior towards Evacuation Time Reduction "

submitted by

Arief Rahman

for the fulfillment of the requirements for the degree of

Masters of Science in Information Technology

Date: ____________

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Date : _____________________________

UNIVERSITI TEKNOLOGI PETRONAS

Agent-Based Simulation and Analysis of Human Behavior towards Evacuation Time Reduction

By

Arief Rahman

A THESIS

SUBMITTED TO THE POSTGRADUATE STUDIES PROGRAMME

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DEGREE OF MASTERS OF SCIENCE IN INFORMATION TECHNOLOGY

Computer and Information Sciences Programme

BANDAR SERI ISKANDAR,

PERAK

NOVEMBER, 2008

DECLARATION

I hereby declare that the thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at Universiti Teknologi PETRONAS or other institutions.

Signature : ____________

Name : Arief Rahman

Date : ___________

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ABSTRACT

Human factors play a significant part in the time taken to evacuate following an emergency. An agent-based simulation, using the Prometheus methodology (SEEP 1.5), has been developed to study the complex behavior of human (the 'agents') in high-rise buildings evacuations. In the case of hostel evacuations, simulation results show that pre-evacuation phase takes 60.4% of Total Evacuation Time (TET). The movement phase (including queuing time) only takes 39.6% of TET. From sensitivity analysis, it can be shown that a reduction in TET by 41.2% can be achieved by improving the recognition phase. Exit signs have been used as smart agents. Expanded Ant Colony Optimization (ACO) was used to determine the feasible evacuation routes. Both the 'familiarity of environment' wayfinding method, which is the most natural method, and the ACO wayfinding, have been simulated and comparisons made. In scenario 1, where there were no obstacles, both methods achieved the same TET. However, in scenario 2, where an obstacle was present, the TET for the ACO wayfinding method was 21.6% shorter than that for the 'familiarity' wayfinding method.

Keywords: Evacuation planning, Prometheus methodology, multi-agent simulation, Ant Colony Optimization, human factors, and cognitive behavior.

ABSTRAK

Faktor manusia mempunyai peranan penting dalam menentukan masa yang digunakan untuk pemindahan semasa kecemasan. Suatu simulasi berasaskan ejen yang menggunakan kaedah *Prometheus* (SEEP 1.5) telah dibangunkan untuk mempelajari kelakuan kompleks manusia (ejen) semasa pemindahan pada bangunan-bangunan tinggi. Untuk kes pemindahan pada bangunan asrama, keputusan simulasi menunjukkan bahawa fasa pra-pemindahan mengambil 60.4% dari Masa Pemindahan Keseluruhan (TET). Fasa pergerakan (termasuk masa beratur) sahaja mengambil 39.6% dari TET. Dari analisis kepekaan, menunjukkan bahawa pengurangan TET sebanyak 41.2% dapat diperolehi dengan menambah baik fasa pengecaman. Papan tanda keluar telah digunakan sebagai suatu ejen cerdas. Pengoptimuman koloni semut yang telah diubah suai (ACO) digunakan untk menentukan laluan pemindahan yang sesuai. Kedua-dua kaedah iaitu kaedah mencari jalan dengan “membiasakan persekitaran”, dimana merupakan kaedah semula jadi, dan kaedah mencari jalan ACO, telah disimulasikan dan perbandingan telah dilakukan. Dalam senario 1, dimana tidak wujud sebarang halangan, kedua-dua kaedah mendapat keputusan TET yang sama. Namun, dalam senario 2, dimana wujud suatu halangan, keputusan TET untuk kaedah mencari jalan ACO adalah 21.6% lebih rendah dari pada kaedah mencari jalan dengan “membiasakan persekitaran”.

Katakunci: Rancangan pemindahan, kaedah Prometheus, simulasi multi-ejen, pengoptimuman koloni semut, faktor manusia, dan kelakuan kognitif.

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ABBREVIATIONS

TET : Total Evacuation Time
SVN : Single Value Network
ACO : Ant Colony Optimization

CHAPTER ONE: INTRODUCTION

The owners of high-rise buildings must have a thorough plan for coping in the event of a disaster, such as fire, earthquake, bomb treat, etc. These plans must take into account the large number of occupants. Measures must be in place to prevent a situation from escalating. There must be adequate emergency facilities. Safe egress of occupants is of paramount importance (Lo, et al., 2002).

Research into emergency evacuation planning and modeling is still a growing area of interest and it has been developed over the last 40 years (Gwynne, et al., 1999). Some challenges in evacuation planning are still open to investigation and some aspects related to human behavior need further study.

The higher the number of occupants of high-rise building, including visitors, the more attention should be given by building management to the safety regulations. Detailed calculations, based on a simulation or other modeling process, are required in order to appreciate the effect that building layout has on the evacuation process. Even a single evacuation drill involving most of the occupants can be expensive. Furthermore, there is an inherent lack of realism, and, therefore, only limited confidence can be placed in any data gathered (Johnson, 2005). A computer based evacuation model has the potential of addressing these shortcomings.

There are several factors that should be considered by building management to design the suitable plan in emergency situations, such as building structures, number and characteristic of occupants, service facilities, building environment, etc. But in general, building management practice focuses on physical anticipations and documentary procedure preparations rather than being more attentive to the impact of human factors on the evacuation process. Human behavior in decision-making significantly affects evacuation time, in both the pre-evacuation phase and the movement phase. Some factors related to human behavior analysis, for the purpose of improving evacuation planning, are provided in this thesis along with some attempts to minimize wasting activities. Some problems faced in the evacuation process are presented in section 1.1.

1.1. Time-Wasting Activities in the Evacuation Process

The time taken to evacuate is the primary measure in assessing the effectiveness of an evacuation process (Gwynne, et al., 1999). Human, as the occupants of high-rise building, with varied behavior and experiences, are the main actors in any evacuation process (Pan, et al., 2006). The complex human behavior should be considered as the main factor in determining the time to evacuate. Some behaviors are potentially problematic and/or time wasting (Purser, et al., 2001). In the movement phase, human behavior must be considered an important factor, affecting speed as well as physical factors of the occupants and the building environments (Gwynne, et al., 1999). Emergency evacuation phases are depicted in figure 1.1.

In pre-evacuation phase, there are three actions that might be taken by an occupant before leaving: being notified about the emergency, start to egress, and selecting the evacuation path. Once the emergency alarms ring, various responses will be evinced by occupants and ignoring the alarm is one possible event that may be taken by the occupant. When the occupants get start to egress, some possible events might be carried out by occupants to save some valuable items or rescue someone else. Although the decision to leave has been taken, some occupants still need much time to confirm the evacuation path or route. The above possible events outline the occupant’s behavior during pre-evacuation phase. Therefore, detailed investigations regarding this behavior should be conducted to improve the performance of the evacuation process.

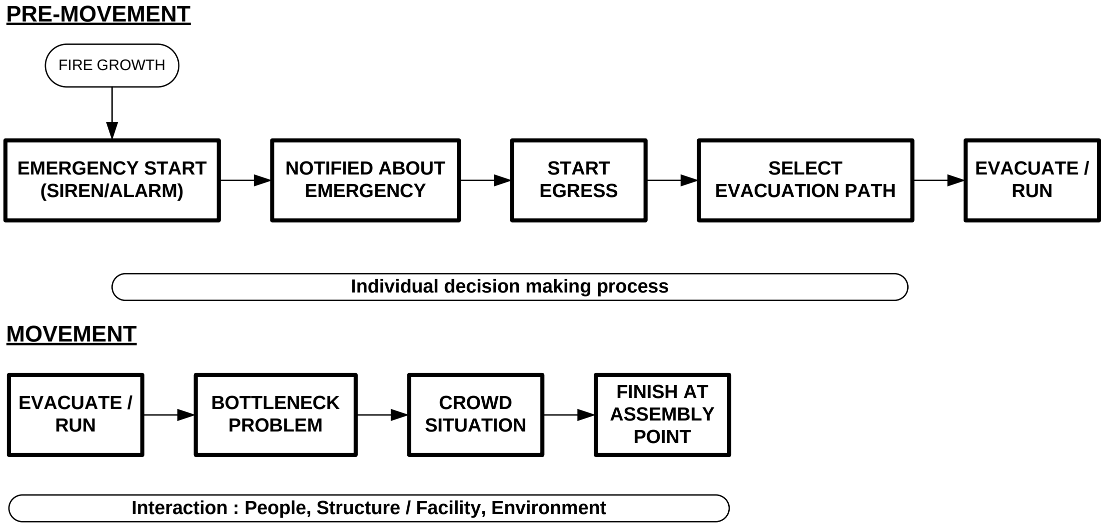


Figure 1.1: Emergency evacuation phases

(Pires, 2005) has introduced an approach to model human cognitive behavior in the very beginning of a fire emergency. This human decision-making approach is the completion of a previous approach and simulation which has not completely presented all the evacuation phases. Moreover, (Proulx, 1995) presents real evacuation drill data in four apartments where 50% of TET is lost during pre-evacuation phase. (Proulx, 1995) stated that occupants tend to ignore the fire alarm and are slow in responding to the emergency notification by continuing their activities. Unfortunately, different building complexity will have different characteristics of pre-evacuation time consumption.

The most complex aspect of people movement in an emergency condition is the approach to select the shortest way out from multi-exit ways in the high-rise building (Lo, et al., 2006). Other than the physical factors, there are some behavior-affected factors on people decision to choose the available routes. These are: familiarity of building environment (cognitive map) (Lo, et al., 2006) (Pan, et al., 2006); interaction and cooperation within the group (Pan, et al., 2006); leadership factor among the occupants (Pelechano, et al., 2006); etc. Guidance or instruction is necessary and important for occupants in panic situations. Exit signs are one type of guidance to find the alternative routes but it is only a static label. A leader among a group of evacuees can also offer guidance and the response from the followers will be higher than with using an exit sign (Murakami, et al., 2002). However, the decision taken by leader is based on the familiarity with the building environment (Pelechano, et al., 2007). Unfortunately, it is not simple to find the leader in every occupant group during a panic situation. Most occupants tend to act more individually and lack the leadership skill to guide others.

1.2. Hypothesis of research

This thesis intends to model human behavior during pre-evacuation using computer simulation. The human cognitive behavior model built into the simulation will give a detailed breakdown of time during the pre-movement phase. The first hypothesis of this thesis is defined as follows, *"Time expended in the pre-evacuation phase significantly contributes to TET due to human behavior"*.

In order to improve the wayfinding method, this thesis proposes a modified exit sign as a dynamic guidance in the evacuation process. Ant Colony Optimization (ACO) is the algorithm used to determine the evacuation route and has been embedded on a modified exit sign. The second hypothesis of this research has been defined as follows, *"Route determination performed by the ACO wayfinding method gives shorter TET compared with the familiarity of environment wayfinding method"*.

A computer simulation with an agent-based methodology has been built in order to present some scenarios to test the research hypotheses.

1.3. Objectives

This thesis pursues two objectives.

1. To study the dynamics of the evacuation process in order to propose some improvements in minimizing TET.
2. To simulate the human behavior in the pre-evacuation phase and its contribution to the length of TET.
3. To study the wayfinding behavior of human for determining the evacuation route.

The emphasis of this research is more on an optimization process of human decision-making during emergency evacuations so as to get minimum TET.

1.4. Methodology

Two proposed ideas are provided in this thesis to improve the evacuation process, i.e.: reducing the pre-evacuation time and proposing the ACO wayfinding. A computer simulation is required to apply some scenarios as a part of the experimental design. Agent-based simulation is developed in our evacuation simulation to present the occupant, emergency exit, corridor/hall, and staircase with their capabilities. In the agent system development, Prometheus methodology is presented to describe the system architectures, the goals, the scenarios, agent's functionalities, agent's capabilities, agent's plan and validation of designed system.

Pre-evacuation time is generated by implementing the human cognitive behavior model. In this thesis, an evacuation survey is conducted to obtain the probability value of each probable event in human cognitive behavior model. This model is built as one of the capability of occupant agent. With this model, our computer simulation, SEEP 1.5, is capable to present the evacuation process including the detail pre-evacuation time. The sensitivity analysis also applied in this thesis to show the influence of probability value against the TET.

The study of the second proposed improvement, ACO wayfinding method, involves the emergency exit agent and occupant agent. Emergency exit agent has the capability to determine the feasible route in evacuation using the ACO algorithm. The expansion of ACO is needed by considering the physical obstacle in the building that needs to be evacuated. With several cycles of experiment using the evacuation simulation, the performance environment familiarity wayfinding method and ACO wayfinding method can be analyzed.

1.5. Scope of Study

Emergency evacuation in high-rise buildings is the focus of the simulation. A student hostel at the University Technology PETRONAS has been chosen as the case study. The maximum number of occupant living in the building is 180. The building has standard safety procedures and standard emergency facilities. The building layout and building dimensions can be found in the technical drawing provided by the university.

In this thesis, some human behavior which has a significant correlation with time-wasting will be studied. Furthermore, the expanded ACO will be introduced with a smart exit sign in the agent-based simulation.

There are some limitations that need to be considered in this research work. All the occupants are normal people with normal capabilities in movement and decision skills. A study related to disable people is not discussed in this thesis. Since age and gender have no significant to evacuation time generation (Proulx, 2005), these two factors will be not discussed in this thesis. The only way to reach the assembly point is through the main exit on the base floor, another exit or staircase on the other floor is not provided. Detailed descriptions of some physical hardware, such as fire detector, movement sensor, smoke detector, as used percept in the simulator, will not discuss in this thesis.

1.6. Thesis Organization

This thesis has been organized into 6 chapters. Chapter 1 and 2 introduce the background of the thesis and chapter 3, 4, 5, and 6 present detail contributions of this thesis.

Chapter **1** presents the context of the research about the emergency evacuation problem in high-rise buildings. Problem statements are presented in this chapter, including the two main objectives of the research.

Chapter **2** describes some backgrounds related to emergency evacuation, human behavior and a multi-agent system in evacuation planning. The standard safety regulation of an evacuation process and the detailed evacuation phases are presented in the first part of chapter. Related human behavior under an emergency situation is presented in the next part. This chapter also presents some terminology the definition about a multi-agent system and some application of agent based simulation in evacuation planning. Finally, some related work about evacuation planning is provided at the end of this chapter.

Chapter **3** presents the model development of the agent-based simulation. Prometheus methodology has been applied to construct the component of the evacuation system. Objectives and hypothesizes of the research have been built in the system specification phase. Some input and also output of the simulation is presented at the end of chapter.

Chapter **4** shows the contribution of this thesis to human behavior studies during the pre-evacuation phase. The results of a survey show the response of people in an emergency situation. By applying a human cognitive behavior model, this thesis has presented some findings about time-wasting activities in the evacuation process.

Chapter **5** presents the main contribution to the evacuation time analysis. Emergency exit sign as an agent has been introduced into the simulation where the ACO is embedded on the emergency exit agent. Human behavior corresponding to ‘familiarity of environment’ has been compared with route determination guided by the emergency exit agent in order to find the feasible evacuation route.

Chapter **6** summarizes the human behavior and its effect on the evacuation time. Some discussions on the findings relative to a reduction in the evacuation time are also presented. Finally, future work is outlined.

CHAPTER TWO: EVACUATION PLANNING AND A MULTI-AGENT SYSTEM: Background & Theories

In the previous chapter, some problems related to human behavior in the evacuation phase were outlined so as to set the context of our research. This thesis focuses on a behavior study in evacuation planning and a multi-agent system is used as the simulation modeling approach. This chapter presents the emergency evacuation standard, evacuation phases, and some human behavior performed in the evacuation process. This chapter also describes the concept of a multi-agent system and some applications of multi-agent simulation in evacuation planning. Finally, we present some related work from previous projects and publications to support our research and development.

2.1. Emergency Evacuation System

The plan for protection of occupants of high-rise buildings must be prepared with precision. Some safety planning, i.e.: adequate evacuation procedures, fire prevention, and emergency facilities planning, are required to prevent any possible disaster happened and to minimize any losses in the event of fire or any other disaster. The potential for accidents to the occupants or maybe loss of life make it essential that evacuation planning and programs must be evaluated and updated continuously. OSHA has defined an emergency action plan (EAP) document for implementation in a safety working environment [29 CFR 1910.38(a)] (www.OSHA.gov).

(Roberts, et al., 2000) has provided list of fire accidents in public buildings in Asia and the USA from 1969 to 1997. As seen in figure 2.1, many people were trapped and killed inside the building and also many of people also got injured due to fire. This clear message cannot be denied and is strong evident that public building management must prevent the building and all the occupants inside from the fire or any possible disaster.

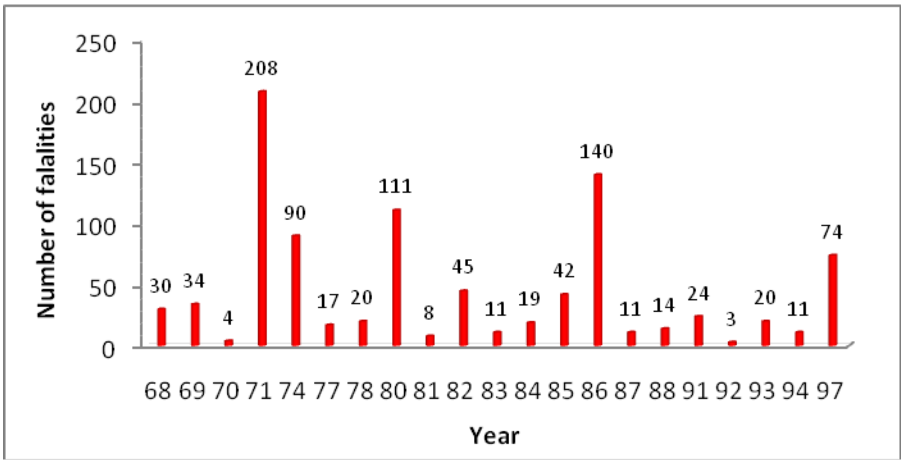


Figure 2.1: Number of fatalities in hotel fires in Asia and USA **(Roberts, et al., 2000)**

A high-rise building is a building with many occupants for any purpose where maximum height of the rescue capability is not able to reach the top level of the building (Pelechano, et al., 2007). Evacuating the entire occupants safely from a high-rise building becomes a special challenge since each building has different problems in evacuation because of different in design, construction, height, floor layout, usage and occupancy. Because of the specific structure of a building, panic behavior of some occupants in the early stages of evacuation can cause fatal accident. To avoid some mistakes and miscommunication during real building evacuation, it is critical to organize, plan, supervise, and conduct periodical evacuation drills in high-rise buildings.

Every occupant in the high-rise buildings must be aware of the building's emergency evacuation policy and plans. These written documents must be distributed to entire occupants by the building management. This procedure is supported and become a standard of OSHA [29 CFR 1910.38(C)(2)], "*An evacuation policy, procedures, and escape route assignments employees/occupants understand who is the authorized to order an evacuation, under what conditions an evacuation would be* *necessary, how to evacuate, and what routes take. Exit diagrams are typically used to identify the escape routes to be followed by employees/occupants from each specific facility location*" (www.OSHA.gov). These documents should describe the fire detection systems, the fire reporting systems, the communication systems, and the emergency evacuation plans provided by the building management. Each floor of the high-rise buildings should have a posted document or information about detailed evacuation routes and the contact number of an emergency officer.

The detailed evacuation route should be included in the building's emergency evacuation plans. By considering the building structure, the nature of the emergency, and scope of the damage, building management and the central evacuation control should determine the safest and best means of building evacuation. Floor number and clear direction of travel should be indicated in every staircase. Safety standard regulation (OSHA) concerning buildings and facilities include floors and aisles, stairways, exits, etc (Asfahl, 1999). In the event of an emergency, all the occupants must follow the building safety procedure and system instructions. As standard, the occupants should exit the work area following the defined evacuation plan, proceed down through the staircase, avoid the elevators and must gather at the assembly point.

With reference to the OSHA standard, each building management or company must an conduct evacuation drill periodically so the occupant is able to recognize the alarm signals and follow the established procedures and evacuation routes. In the event of fire or any disaster, the occupants should be able to locate where the alarm system position and should be trained to contact the emergency number. People movement during evacuation should be monitored by a safety officer or a floor warden including identification of occupants with special needs or disabilities who may need help in evacuating (Asfahl, 1999). An assembly point or meeting location must be determine by an evacuation planner and each area should have an assembly point, where occupants can gather, counted and alert the emergency officer if anyone is missing.

A written escape strategy for an emergency evacuation must be prepared to cope with fires or other disasters. It is important to develop an emergency alarm system as a part of the escape plan. However developing the alarm systems are not simple, the evacuation planner must consider the system reliability and also the people response. In fact, not all occupants will recognize the signal as a fire alarm (Pires, 2005). Sometimes, direct voice communication or a sounder may be the best fire alarm medium (Purser, et al., 2001). The reliability of the fire alarm system is essential since a failure within the system may not be immediately obvious. Some sensors like smoke detection, temperature sensor, and other devise may be used as the alarm. (Asfahl, 1999)

The movement of occupants in an evacuation can be controlled through modern communication technology. Depending on the complete and accurate communication between the evacuation control and all floor-evacuation control teams, it is possible to evacuate an entire building with proper movement to the assembly area (Asfahl, 1999). Opportunities to enhance the communication system in evacuation planning exist due to the growing use of information system applications, optimization methods, and mobile communication and advanced communication technologies. An expert system, as a part of artificial intelligence, has been applied to many applications related to the evacuation system enhancement. The intelligence capability of the computer system and the roles used should be able to represent real human action and behavior in an emergency evacuation.

2.1.1. Evacuation Phases

There is much literature that presents the components of an evacuation process (Chow, 2007) (Gwynne, et al., 2005) (Proulx, 1995) (Thomson, et al., 1995), (Lo, et al., 2002) (Purser, et al., 2001). Most of it agrees that at least there are two main phases in evacuation, these are the pre-evacuation phase (response) and the movement phase (evacuate). However, in simulation or experiments, some existing studies did not consider all the parts of evacuation time.

The main objective of an evacuation process is to save all the people in the building as fast as possible. Even though many researchers have different terminologies, the main indicator of emergency evacuation is Total Evacuation Time (Chow, 2007) (Gwynne, et al., 2005) (Helbing, et al., 2000) (Kisko, 1999) (Olsson, et al., 2001) (Proulx, 1995) (Pelechano, et al., 2007) (Purser, et al., 2001). Because of some different interpretation in how to calculate the TET and its components of time, it is necessary to refer some related literature in order to clarify the definition of TET.

(Proulx, 1995) has specified TET as two main components, time to start and time to move (time to evacuate and pass though the exit). So, according to (Proulx, 1995), the escape movement time (T) is equal to time to start the movement (t_1) plus the time to move and pass through emergency exits (t_2). It is not just simply T equal to t_2.

The evacuation time should be considered the queuing time. However, queuing is not appropriate to describe the time taken for movement. The time to queue should exclude the time to move because occupants do not move during the queuing process. (Chow, et al., 2007) and (Chow, 2007) also define TET as being made up three components of time; these are response time (t_{rest}), travelling time (t_{trav}) and waiting time (t_{wait}). Figure 2.2 shows the detailed components of evacuation time provided by (Chow, et al., 2007).

$$\mathbf{TET = t_{rest} + t_{trav} + t_{wait}} \qquad \mathbf{(2.1)}$$

The calculation of TET begins when the occupant decides to leave the building and it will be end until the occupant exits the building. The duration before the occupant decides to leave the building will be not considered as a part of TET.

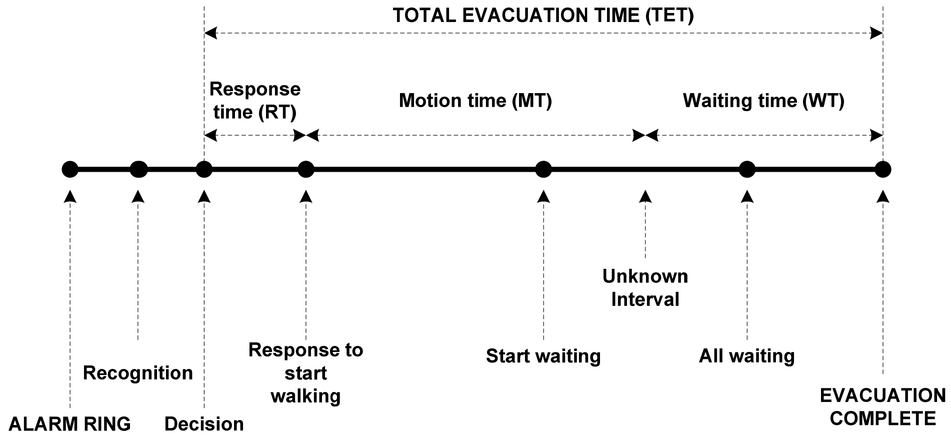


Figure 2.2: Evacuation time line

Nonetheless, (Pires, 2005) who studied pre-evacuation time behavior stated that evacuation modeling should approach the decision making process at the very beginning of an emergency conditions. Time to start or response time should be defined start from the event of an alarm ring because during the pre-evacuation phase, there are some actions will be taken by occupants. This idea is supported by (Purser, et al., 2001) who defined the pre-movement phase beginning from the alarm ring or cue and ending when travel to exit. Based on those references, it is necessary propose the modification of the evacuation time line and TET's calculation provided by (Chow, et al., 2007). (Purser, et al., 2001), states that the recognition time (On) start at the alarm ring and end with the first response given by an occupant, and response time start at the first time response of occupant and ends when the occupant starts to leave. Finally, the modification of the evacuation time line to calculate the TET has been provided in figure 2.3.

Pre-evacuation time should be considered three possible actions and formula 2.2 presents the redefinition of the pre-evacuation time calculation.

$$\mathbf{T_{rest} = t_{On} + t_{Se} + t_{Cp}} \tag{2.2}$$

t_{On} = time taken by occupants during recognition process

t_{Se} = time needed by occupants for preparation actions before leaving

t_{Cp} = time allocated for as possible action to investigate the evacuation route

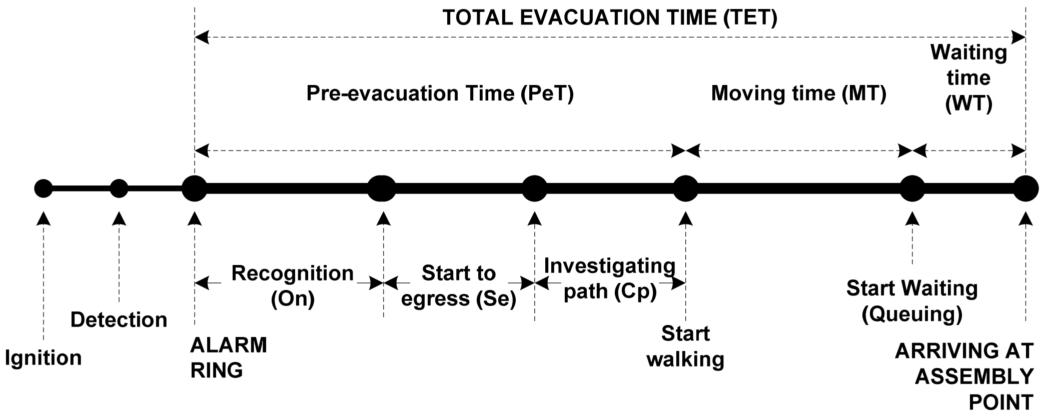


Figure 2.3: Evacuation time line where TET start from alarm ring event

2.1.2. Human Behavior in an Evacuation

Humans as the main actors in an evacuation display various types behaviors. It is common in an evacuation for there to be overcrowding. Overcrowding is natural behavior where people tend to move together in group and crowd together. There have been many disasters occurring in high-rise buildings as has been reported around the world, which have caused many people to be killed or suffer in permanent injuries. The biggest fire accident, WTC attack in USA, killed at least 2900 people (2001), a night club fire in Buenos Aires, Argentina, killed 194 people (2004), a stampede incident in Ghana, Africa, killed 120 people (2001), the Amsterdam Schiphol Airport fire killed 11 people (2005), and many other building fires have been reported (www.Wikipedia.org).

(Pan, et al., 2006) also provides some facts that “non-adaptive” behavior has caused more victims in a crowded evacuation rather than the actual danger such as the fire. They provide some accidents to prove the impact of “non-adaptive” behavior on an evacuation, such as the crowding accident at Iroquouis theatre in 1903 where 602 killed and the English FA cup stampede in 1981 which killed 95 people and more than injured more than 400 people because of ‘non-adaptive’ behavior. Non-adaptive behavior tends to be classified as negative behavior in a crowd and some of examples of this behavior include pushing, stampeding, knocking, and trampling.

This thesis focus on behavior related to the scope of the research. Some behavior is relevant to the decision-making process during the pre-evacuation process and behavior related to escape strategy in the movement phase will be classified as shown below.

A. Panic

A life threatening situation in the event of fire or any other disaster can be a triggered event of panic, which could possibly lead to accidents or fatalities of human lives because of crushing or trampling (Helbing, et al., 2000). When some clues are received followed by a perception of a dangerous situation, people often act irrationally unless they have a strong positive social personality such as leadership capability (Pan, et al., 2006). Summarizing by (Helbing, et al., 2000), there are several characteristics of panic in the evacuation process.

- People are disposed to run or speed up their walking. They walk faster than their normal speed.
- Pushing and physical interaction among the occupant might be happened as a natural reaction.
- People move in an inconsistent direction and are eager to run away faster by passing the lead occupant.
- Sometimes, arching and clogging behavior happens at an exit emergency.
- Because of overcrowding and uncoordinated movement, bottlenecks often happen in some exits or preparation areas such as corridors and balconies.
- With the high pressure built up by a jammed crowd during a bottleneck, it is possible to make a brick wall fall down.
- Disabled people or injured occupants walk slower than normal people.
- Most people will take a group decision or just followed the majority (mass behavior).
- Sometimes the alternative escapes or exits are not properly used.

A people who fall into a panic tend to act with some non-adaptive behavior and may cause an uncontrolled evacuation process. Even this behavior is difficult to control during uncertain situations, providing well prepared communication between occupants and the evacuation control, people might gain the confidence to exit safely. The important of guidance during a crowd situation is absolutely necessary as one of the alternatives in avoiding panic behavior.

In a panic situation, people move with dynamic movement where the velocity is influenced by some particular forces. Dynamic movement is defined as the acceleration of movement. Referring to (Helbing, et al., 2000), there are two forces that influence movement, i.e. socio-psychological and physical forces. Naturally, the velocity of people movement depends on the distance from other occupants and also the distance from the physical building structure such as the wall and the exit.

Dynamic movement presents a direct interaction between the human and a physical object in the building. The acceleration equation (2.3) describes the change of person's velocity in time *t*.

$$m_i \frac{dv_i}{d_t} = m_i \frac{v_i^0(t).e_i^0(t) - v_i(t)}{\tau_i} + \sum_{j(\neq i)} f_{ij} + \sum_{W} f_{iW} \quad \text{........................} \mathbf{(2.3)}$$

while the change of position $\boldsymbol{r}_i(t)$ is given by the velocity $\boldsymbol{v}_i(t)=d\boldsymbol{r}_i/dt$.

m_i : mass of people i

$v_i^0 e_i^0$: certain desired velocity of people i into a certain direction e_i^0

v_i : actual velocity of people i

τ_i : a constant for time acceleration

(Helbing, et al., 2000) describes the above acceleration equation with more detail of the psychological forces (2.4). There are three forces that influence the interaction between people, i.e. a repulsive interaction force, a body force and a sliding friction force.

$$f_{ij} = \{A_i \exp[(r_{ij} - d_{ij})/B_i] + kg(r_{ij} - d_{ij})\}\eta_{ij} + \kappa g(r_{ij} - d_{ij})\Delta v_{ij}^t.t_{ij} \quad \text{................} \mathbf{(2.4)}$$

where

$d_{ij} = \|r_i - r_j\|$: distance between the occupant's center of mass.

$\eta_{ij} = \frac{(r_i - r_j)}{d_{ij}}$: normalized vector pointing from occupant j to i.

A_i and B_i : constants to keep on normal desired velocity and fit the measured flow

k & κ : parameters to determine the obstruction effects

And the force between the occupants and the physical building structure, such as a wall (W) is given by (2.5).

$$f_{iW} = \{A_i \exp[(r_i - d_{iW})/B_i] + kg(r_i - d_{iW})\}\eta_{iW} - \kappa g(r_i - d_{iW})(v_i.t_{iW})t_{iW} \quad \textbf{(2.5)}$$

where

d_{iW} = distance between occupant and the wall

t_{iW} = direction tangential to the wall

It has been shown that escape panic has a direct correlation with the velocity of movement. Interactions of an occupant with the other occupants and with the physical building structure influence the velocity of movement. Behavior during movement such as the desire to increase walking speed, herding, strong frictions, etc has been considered by (Helbing, et al., 2000) and should be useful in people movement simulation, especially in evacuation planning. This pedestrian interaction model will be considered in our simulator development.

B. Wayfinding

Quoted from (Pelechano, et al., 2006), "*Wayfinding is the process of determining and following a route to some destination*". This process needs the cognitive component of navigation and building knowledge to determine the route based on the initial position to the targeted position. This behavior can be classified on decision making categories (Pan, et al., 2006). According to (Pelechano, et al., 2006), there are four components influence the wayfinding during the evacuation process. These are as follows:

- Cognitive map (a mental model of space)
- Orientation (its current position within the cognitive map)
- Exploration (processes to learn the features of the space (doors, walls, hazards, etc))

- Navigation (process to move through the environment)

From a human psychological point of view, behavior presented by a human is apart of his/her decision making process. Furthermore, (Pan, et al., 2006) has classify the individual decision making processes in evacuation into three basic conventions, those are 'following instinct', 'following experience' and 'bounded rationality'.

'Following instinct' is the most primitive decision taking by people in making an instantaneous or quick response (Pan, et al., 2006). Pushing others to escape to the blocked exit is behavior brought about by fear. Naturally, humans are able to retrieve their past experience and follow their habitual activity or repetitive events in making decisions. In an evacuation process, the experience of an occupant has significant correlation with their behavior in responding to the emergency situation in the building (Pan, et al., 2006). The familiarity of a building environment, knowledge related to the safety procedures and evacuation drill experiences are some life experiences which directly influence their decision during an emergency situation. An occupant of a high-rise building will be able to determine the shortest route according to their routine or what they are most familiar with, but a negative response can result from the occupant ignoring alternate routes. 'Bounded rationality' or rational decision making is a decision-making process which compares and evaluates alternative of solution with their consequences and also depends on personal preference (Pan, et al., 2006). This type of decision process takes longer and in an emergency evacuation this type may not be an appropriate one to take, as people will make the decision instantly.

Getting the wayfinding in an evacuation is also influenced by collective action in crowds. An individual tends to follow the group of people when choosing the evacuation routes (Pan, et al., 2006). The kin behavior can be classified as a group behavior in evacuation where a group member (e.g.: family member) usually insists on gathering together. Sometimes, when a member of a group is separated, the group leader may seek and trace back the previous route to track the lost member then it is called as backtracking phenomenon (Yang, et al., 2005). In group behavior, the most experienced people to building environment usually become the leader of the group and the group leader plays an important role in the evacuation route determination. We present some related work about leader contribution in an evacuation on sub chapter 2.2.2.

C. Ignoring immediate leaving

To date, few studies in existing literature have observed and analyzed human behavior during the pre-evacuation phase. Whereas, previous observations in evacuation drill has showed that some types of behaviors waste time during the pre-evacuation phase. According to the OSHA standard procedure, once the emergency status is apparent, all the occupants excluding the safety officer or floor warden must decide to evacuate immediately. On the contrary, some previous studies presented by (Proulx, 1995), (Ko, et al., 2007) and (Olsson, et al., 2001) and also our evacuation survey results show that major occupants will not heed the emergency notification. This behavior is called ‘ignoring immediate leaving’.

There are three reasons presented by (Proulx, 2000) why occupants ignore immediate leaving. First, some occupants fail to hear the fire alarm signal since their origin location is not provided with standard alarm or is far from the source of the alarm signal. Second, occupants do not evacuate when they hear the true the alarm signal because they perceive it as a nuisance alarm. They might consider the sound of the alarm to be a false alarm, a test alarm, or a fire drill event. Third, there is a possible situation where untrained or new occupants fail to recognize the alarm signal as the real danger.

There are several actions showed by occupants before decide to leave the building and (Pires, 2005) in his cognitive behavior modeling approach has classified those actions into three possible actions. Those are recognizing the emergency conditions, start to egress, and investigating a path to take (please see sub section 5.3. for detailed description). (Proulx, 1995) also described some actions of people before leaving, i.e.: finding children/pets, gathering valuables, getting dressed, having a look out of the window or contacting the reception/building officer to get confirmation, moving to balcony, and securing important documents or data.

‘Ignoring immediate leaving’ tends to create several activities which are potentially time-wasting. Unfortunately, few field observations and evacuation simulators present this phase.

2.2. Multi-Agents System

The use of intelligent agents has grown fast during last decade and many applications have been built using agent orientation. Agent-based systems have spread widely in artificial intelligence and have significant implementation in generic computing technology. Agents in a computer system are designed with autonomous flexibility and developed in an open environment. As an autonomous system, agent-based system have also contributed in communication and e-business application development, where agents have supported the automation of information gathering and automatic purchase transaction over the internet.

2.2.1. Definition of Terminology in Multi-Agent System

Nowadays, there are many different labels for agents: autonomous agents, software agent, intelligent agent, interface agent, technology agent, virtual agent, etc. Many diverse areas such as computer science, social science, economics, production, human factors, etc are involved in multi-agent systems. The multi-agent systems are formed from different knowledge and it is highly interdisciplinary (Wooldridge, 2002). (d'Inverno, 2004) defines some terminology about agents as shown below.

- An agent is an object with goals and an autonomous agent is an agent with motivations.
- An object is an entity with a non-empty set of actions.
- A multi-agent system is any systems that contain (1) two or more agents; (2) at least one autonomous agent; and (3) at least one relationship between two agents where one satisfies the goal of the other.

Alternatively, (Wooldridge, 2002) defines an agent as a computer system that is situated in some different environment and has an autonomous capability to adapt for the different environment to achieve its design objectives. (Giorgini, et al., 2005) defines a multi-agent system as a group of cooperative or competitive agents which interact to achieve the specific goals. According to (Satria, 2003), a multi-agent system is a system development paradigm where several agents in the system community interact, negotiate, and coordinate with each other to operate the task with a specific goal. From these definitions, it can be concluded that at least three main characteristics of agents can be concluded, i.e. have a specific goal, autonomous, and able to interact with its environment and other agents.

An agent as an intelligent object has specific characteristics and attributes.

- **Autonomy**

  Agent should be able to operate and complete their job without the need for human guidance and its action is not determined by the outer environment (Nwana, 1996) (Satria, 2003) (Wooldridge, 2002) (Xiang, 2002). An agent has to be independent (Giorgini, et al., 2005) (Padgham, et al., 2004), and able to control its action.

- **Intelligence, Reasoning and Learning**

  The minimum standard for agent capable of intelligence includes an internal knowledge base, a reasoning capability and a learning ability to adapt to unpredicted conditions (Satria, 2003) (Padgham, et al., 2004).

- **Mobility and Stationary**

  A specific characteristic of mobile agents is their flexibility to communicate and send information during their actions around some network (Nwana, 1996). Henceforth, a stationary agent has less flexibility to communicate during the action (Satria, 2003). This characteristic is optional and describes a special subtype of agent (Giorgini, et al., 2005).

- **Delegation**

  The main characteristic of agents is their capability to handle and offer the instruction or information as a delegation process. The Agent will act base on the user's instruction (Satria, 2003).

- **Reactivity or Learning ability**

This dynamic characteristic enhances an agent is capability as an immediate response to their external environment (Satria, 2003) (Nwana, 1996) (Giorgini, et al., 2005) (Wooldridge, 2002).

- **Pro-activity and Goal-oriented**

  An intelligent agent should not only be reactive to the environment, but should be able to take a new initiative in order to solve the problem (Giorgini, et al., 2005) (Wooldridge, 2002). An agent should have clear goals or objectives and goal oriented action (Satria, 2003) (d'Inverno, 2004) (Padgham, et al., 2004).

- **Social ability**

  Agent-to-agent and agent-to-user communication and coordination should be defined based on the objective of agent interaction (Wooldridge, 2002). Cooperation with other agents is paramount (Nwana, 1996), interaction with user and also among the agents is a must in multi-agent systems, so an agent needs to possess this social ability.

These characteristics of agents have been supported by some related research areas as depicted in figure 2.4. A multi-agent system has to combine and collaborate different methods and knowledge in order to develop real agents for realistic modeling. Social sciences, psychological approaches, human factor analysis and decision theory become the fundamental systems in multi-agent development.

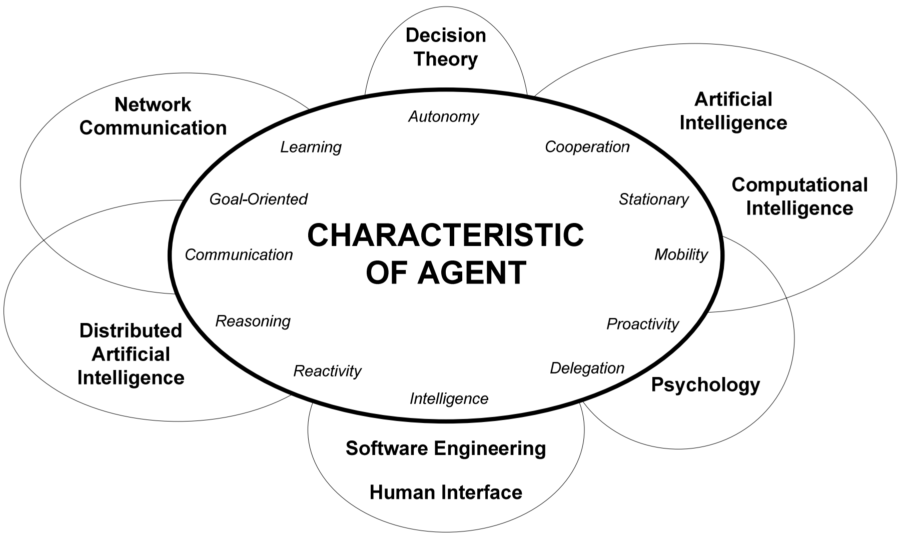


Figure 2.4: Characteristic of agents and related area of studies

(Nwana, 1996) uses three main characteristics in figure 2.5 to derive four types of agents to build in agent topology: Smart agent, Collaborative learning agents, Collaborative agents and Interface agents. Complete characteristics of agents are embedded on a smart agent, it is able to learn the environmental changes, cooperate with other agents, and have an autonomous character to control its objectives.

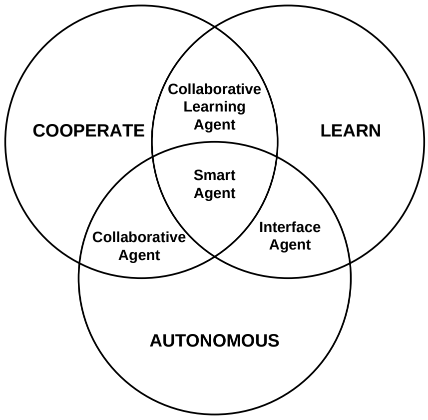


Figure 2.5: Part of the view of agent typology

Furthermore, (Wooldridge, 2002) states a clear definition about intelligent agents. An intelligent agent is an agent which has the intelligence characteristics i.e. reactivity, pro-activeness, and social ability. An intelligent agent perceives its real time situation in the surrounding environment and adjusts its objectives with environmental changes (reactive). An intelligent agent creates initiative actions to exhibit goal-directed behavior in order to achieve its objectives (proactive). An intelligent agent interacts with other agents in order to achieve its objectives (social ability).

Whilst there are some similarities between objects and agents, there are some significant differences between them. An object is an entity with some states enclosed in a computer system, able to perform some actions or functions, and able to communicate by message elapsing. (Wooldridge, 2002) has summarized the distinctions between agent and object; there are three significant differences between them.

- An Agent presents a stronger notion of autonomy than an object and is able to decide its actions by itself with or without any interaction with others.

- An agent has a flexibility of behavior in an environment situation. An object model has no such complex behavior.

- A multi-agent system is inherently multi-threaded, in that each agent is assumed to have at least one thread of control.

Prometheus, as the agent methodology for agent-based simulation development, is described in chapter three. It is used in the emergency evacuation case study.

2.2.2. Multi-Agent Systems in Evacuation Planning

In this subchapter, earlier work related to evacuation computer modeling using multi-agent approaches is presented. Other related references using a different approach will be discussed in the next subchapter.

Multi-agent based simulation has been applied widely in many applications including crowd simulation in the evacuation process. Multi-agent systems are appropriate to represent humans with their complex decisions and behavior. In evacuation simulation, an occupant is represented by an autonomous agent and this agent is proficient in receiving and sending any data to the environment. Some other agents should be created to represent some building facilities, i.e.: exits, exit signs and an assembly point. In the system architecture, those agents have the detailed plans or procedures with some rules bases to represent the interaction between the agents and each agent also has an individual plan to represent the autonomous capability of the agent. As depicted in figure 2.6, four types of agents may involve in evacuation simulation.

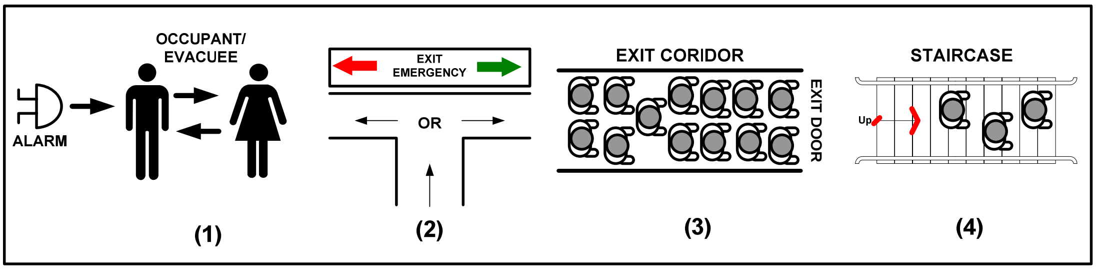


Figure 2.6: Occupant and building facilities as involved agents in evacuation **(Pelechano, N., & Malkawi, A., 2007).**

(Pan, et al., 2006) developed a multi-agent simulation as a basic scheme in evacuation planning where some human behavior was attached to the occupant agent. The simulation is built with six basic components, i.e.: geometric engine, population engine, the global database, the event recorder, the visualizer, and the crowd simulation engine. Six basic components of simulation modules are depicted in figure 2.7. The geometric engine presents the building environment and structures. The population generator is a module which produces the occupant population with some specific attributes and this module also generates type of facilities. The global database handles all data transaction in the simulation as interaction and reaction between the occupants. The events recorder captures and retrieves all events during the simulation and the visualizer shows the result of the simulation. (Pan, et al., 2006) stated that the core module is the crowd simulation engine where there are three main behavior models embedded on the systems; these are locomotion behavior (walking forward, running forward, stopping, side-shifting, turning and moving backward), steering behavior (walk, collision, seek, negotiation, and target following) and social behavior (competitive, queuing, herding and bidirectional flow).

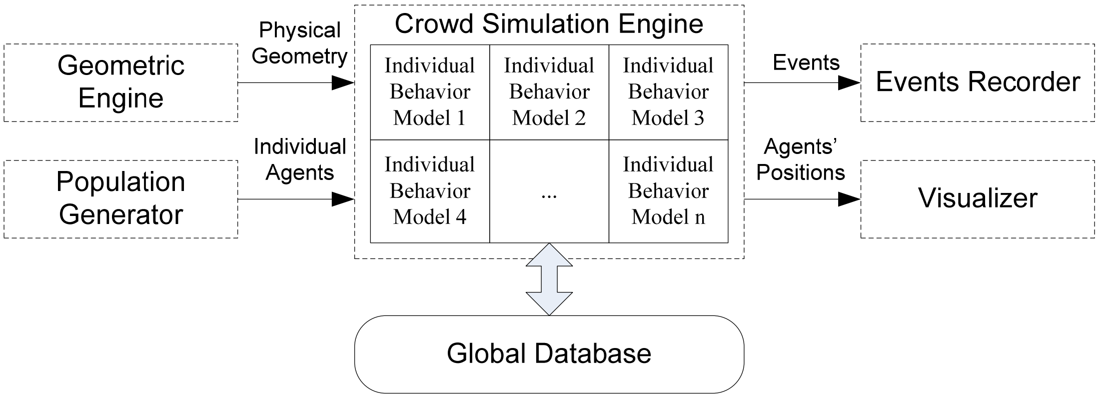


Figure 2.7: Evacuation system architecture developed by **(Pan, et al., 2006)**

An occupant with good familiarity about the environment and good evacuation training experience should be able to share information with other occupants and be a competent route guide during evacuation process. In order to study the leadership contribution in an evacuation process, (Murakami, et al., 2002) has introduced a leader in their simulator. The multi-agent system has been modified to represent the interaction among leaders and other occupants. They compare the output from the simulator using FlatWalk with the Sugiman real experiment results. The multi-agent simulator, FreeWalk (the 3D simulator) and Flatwalk (the 2D simulator) adopted to simulate the evacuees and leader, where each individual has their own behavior and response in order to reach the nearest exit. There are three scenarios has built in to their experiment, these are *follow-direction method* (leader show the route based on his/her knowledge), *follow-me method* (leader take the evacuee to the exit), and *scenario for evacuees* (response actions toward the leader message or position). These action rules were extracted from observation of an evacuation drill video tape and interview response analysis. Learning from this simulation and experiment, it shows that the leader has a positive impact in increasing the performance of people movement. Four leaders leading 16 evacuees performed a faster evacuation time with the follow-me method compared with the other methods. (Murakami, et al., 2002) stated that some evacuees getting confused at the starting period because they receive many instructions simultaneously from different leaders. (Murakami, et al., 2002) also highlighted the importance of real world feedback to verify the simulation output.

Another application of multi-agents was presented by (Pelechano, et al., 2006) where an occupant agent played the main actor in the simulation. The project objective is to simulate the leader behavior during evacuation. The agent leader has the capability to lead the other occupants by performing high-level wayfinding using a cognitive map of building. A computer simulation, Maces (Multi-Agent Communication for Evacuation Simulation), has been developed to present people movement with Helbing's acceleration model. Each agent has different behavior which depends on the leadership and the training experiences. The high-level wayfinding algorithm consists of three main steps.

1. The leader shares his/her environment situation and structure with other occupants.
2. The occupant agent checks the shortest path which is shared by the leader.
3. An obstacle appears, the agent react with different responses depending on their training experience and leadership capability, untrained agents act as follower agents and will follow an agent with leader capability.

A detailed description of the wayfinding decision flow is depicted in figure 2.8.

Based on (Pelechano, et al., 2006) simulation where 200 agents were involved, communication amongst the agents during evacuation resulted in a faster evacuation than without any communication. (Pelechano, et al., 2006) conclude and explain that higher number of trained agents means faster the evacuation time to be accomplished. Leadership factor shows similar influence effects like training attributes, more number of leaders than faster the evacuation time.

Leadership aspect and other human responses in evacuation process is also represented by (Sugimoto, 2005) using agent in virtual participatory simulation. Participatory simulation is such that avatars manipulated by humans are arranged in multi-agent simulation, in which interaction among humans and agents are permitted. World state simulation using avatars has been built including agent behavior and interaction rule.

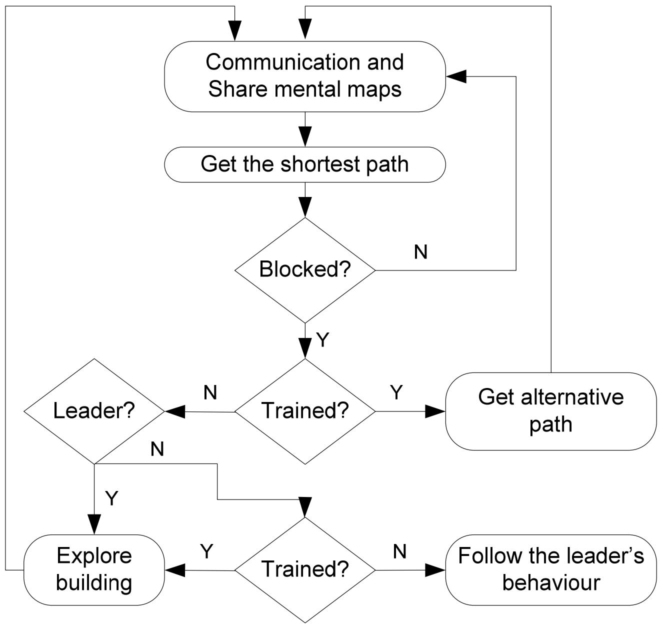


Figure 2.8: High level wayfinding step introduced by **(Pelechano, et al., 2006)**

2.3. Prior Researches in Emergency Evacuation Modeling

This section presents a summary of relevant studies to emergency evacuation modeling and also human behavior during evacuation process. In subchapter 2.2.2, some previous works in evacuation planning using multi-agent system has been provided and this part presents some previous works which not applied the multi-agent system.

Complete information related to people movement and complex human behavior in evacuation process is difficult to represent. Evacuation drill is one of alternative to demonstrate the evacuation process even this exercise still far from real situation (Gwynne, et al., 1999). (Proulx, 1995) has provided the emergency evacuation experimental result from four buildings (6-7 levels) with average population of 150 occupants. They observed the people movement through video camera and also took some response with some interviews.

Age and gender are two factors that should be considered in TET estimation. Surprisingly, (Proulx, 1995)'s experiment shows that the age and gender has made no significant difference to evacuation time generation. During movement, gender has very little influence to the time to evacuate and man took longer time generally but it was not significant different. Age also showed very few significant differences between the groups of age, some case showed the younger moved faster but the older have faster movement in starting period and small children is the slowest groups during evacuation.

Real observation of evacuation process in three university buildings is also presented by (Olsson, et al., 2001). With (Olsson, et al., 2001)'s real observation, SIMULEX (Thomson, et al., 1995) has been compared in reaching the real world problem and SIMULEX has been performed with confidence to simulate evacuation process. But for pre-movement phase, it seems to be conservative in comparison with real measured time. A validation of computer simulation with trial evacuation was also performed by building-EXODUS (Gwynne, et al., 2005). The Stapelfeldt experiment involved 100 police cadets and The Milburn House evacuation experiment involved 381 people have been simulated with some scenarios applied. It has been highlighted that sufficient data from real evacuation exercise is the important matter to consider in a simulation model validation.

Another comparison between trial evacuations with commercial simulation model and with their own simulation model was presented by (Ko, et al., 2007). Two storey office buildings, one factory and one warehouse with more than 100 people involved were chosen as the trial evacuation site in New Zealand. TET produced by SIMULEX has performed quicker result and EvacuationNZ (developing model) able to reach closer TET compared to actual trail evacuation result. EvacuationNZ has considered the pre-evacuation time with normal distribution time generation and ±10 seconds variation in mean. Furthermore, (Ko, et al., 2007) has showed that pre-evacuation time is necessary to reach the appropriate simulation time against the real evacuation time.

Quantification of behavior in evacuation is presented by (Purser, et al., 2001) with three real fire emergencies and five evacuation studies. Pre-movement is the important phase in evacuation process and it has taken the greatest part of evacuation time but tend to be improved with good fire safety systems. Furthermore, (Purser, et al., 2001) presents that the pre-evacuation time distribution tends to be skewed and fit with log normal distribution. The frequency distribution of TET appears to fit with normal distribution.

Moreover, (Pires, 2005) has proposed a probabilistic model to estimate the cumulative probability start to egress in pre-evacuation process. (Pires, 2005) also construct the probability equation to predict the human stress level using Bayesian Belief Network. (Pan, et al., 2006) also has developed a prototype model using multi-agent system to model the non-adaptive crowd behavior in evacuation planning. This computational framework is able to model emergent human social behavior, such as competitive behavior, herding behavior and bidirectional crowd flow. Since this cognitive behavior model has not been developed yet, a challenge is offered to present this model into simulation.

Some works have been done in investigating the wayfinding methods. Some theories and methodologies related to wayfinding problem have been presented by (Lovas, 1998). The Hampton court maze is presented to compare the performance of wayfinding methods: random choice, follow planned paths, directional choice, shortest path, and frequently used paths. A computer simulation EXIT89 has been developed with wayfinding capability. Compared to other computer simulation in evacuation, EXIT89 is able to explore the evacuation routes. Simple shortest route algorithm is combined with individual perspective to track the path. Unfortunately wayfinding method of EXIT 89 is unable to perform the significant result. Occupants from certain nodes will travel with the same route specified by user or the shortest known path, to the exit (Santos, et al., 2004).

As previous presentation, leader as a guide in agent simulation in evacuation can be considered as wayfinding method study. Leader in the event of emergency has also been considered as an influence factor during movement phase to reach the exit. (Pelechano, et al., 2006), (Murakami, et al., 2002), and (Sugimoto, 2005) have presented their research contribution in modeling human as a leader in evacuation. However, based on (Pelechano, et al., 2006)'s finding, at least 10% of total occupants should be trained as a leader. Availability and capability of leader in evacuation must be considered by evacuation planner.

2.4. Discussion on Research Gap

This section present some discussions based on previous studies on research gaps.

Since there are many different presentations about the evacuation phases from previous studies, these presentations must be discussed to obtain a clear definition for the evacuation study. Evacuation timeline proposed by Chow (2007) has provided a good graphical presentation of detailed process. Unfortunately, in this work the TET is counted from the event involving people's response. This point of view was conflicts with Purser, et al. (2001) and Pires (2005)'s who proposed the determination of evacuation time from the event of the first emergency notification. It is also important to consider any possibly events due to response time calculation. Pires (2005) has proposed a new model which associated human cognitive behavior with the event of evacuation. Based on Pires' model, we have defined the detailed calculation during the pre-evacuation phase or time before movement. TET will be determined starting from the event of alarm ring. This modification has been presented in figure 2.3.

Previous evacuation drill conducted by Proulx (1995) and Purser, et al. (2001) have emphasized that pre-evacuation phase must be considered as the important phase in evacuation. In contrast, this important part of evacuation tends to be ignored by most of existing evacuation simulation. The main reason of this simplification is the difficulties of presenting human behavior during the pre-evacuation phase. In this case, time generation via the random number generator is the simplest procedure to present the pre-evacuation phase. Therefore, the study of pre-evacuation time generation is a challenge to present the important of pre-evacuation phase to the TET. Pires (2005) has introduced his probability model to explain the importance of the pre-evacuation process. This model has not been implemented yet using any computer simulation, as such provides a research opportunity presented in this thesis.

The application of multi-agent system on evacuation planning has grown so fast since this approach is capable to handle the complexity of human modeling. There are some examples of multi-agent simulations in evacuation as presented in previous sub chapter. They should apply appropriate agent-based methodologies but none of them describe the detailed development of evacuation model. A Prometheus methodology, as one of agent-oriented methodologies, has a number of strengths as compared with the other methodologies. This methodology has not applied yet for emergency evacuation study. Applying Prometheus methodology in evacuation problem can be one of challenge and become a significant contribution for agent-oriented software development.

As stated in the background of this research, the importance of guidance during the movement phase has been presented and also supported by some reviews from the previous studies. Leader has been simulated by Murakami, et al. (2002), Sugitomo (2005), and Pelechano (2006) as the improved guidance in the movement phase. From their observation and simulation, the leader has a significant contribution on the wayfinding process. However, the availability and the capability of leader in evacuation will become the future problem to be adjusted. As such, it provides a research opportunity for the enhancement of leader presented in this thesis to adjust the leader's limitations in providing dynamic guidance during the evacuation process.

2.5. Summary

This chapter has presented two related research fields addressed in this thesis, i.e.: emergency evacuation system and MAS. The importance of emergency evacuation is discussed in the first part of this chapter. Some standard regulation refers to ISO and OSHA is described to support our evacuation model development. Some reviews about evacuation phases are provided to strengthen the TET definition and calculation. Evacuation phase is divided into two main phases, i.e.: pre-movement phase and movement phase. In pre-movement phase, there are three main activities of occupants these are recognition of alarm signal, start to egress, and investigating path.

Some reviews related to human behavior study in evacuation process are presented: panic, wayfinding, and ignoring immediate leaving. Some reviews about application of MAS in evacuation planning and simulation are provided with detail model description. This chapter also provided some previous references related to our research.

The next provide the model development of evacuation simulation with hostel evacuation as a case problem. The implementation of evacuation simulator will be presented in detail on the next chapter.

CHAPTER THREE: DEVELOPING AGENT-BASED SIMULATION IN EVACUATION PLANNING

The previous chapter presents some backgrounds and related works about evacuation planning and model development. In this chapter, agent-based modeling in evacuation is presented using Prometheus methodology. In detailed design phase, this chapter describes the agent properties and characteristics with Prometheus Development Tools (PDT) 3.1. Implementation and validation of simulation model have been provided to complete the model development.

3.1. A comparison of Agent-Oriented Development Methodologies

There have been several tools and methodologies introduced for agent systems development. (Al-Hashel, et al., 2007) has presented a comparison between three different agent-oriented methodologies; these are MaSE, ROADMAP, and Prometheus. These three methodologies have different focus of agent applications, Prometheus has systematic phase to build intelligent agents, MaSE is suitable for multi-agent system with heterogeneous membership of agents (Tran, et al., 2005), and for course grained computational agents, it is recommended to apply ROADMAP (Al-Hashel, et al., 2007). From the scale of details point of view, Prometheus has provided complete phase with detailed specification. Prometheus has clear concept to present agent with high autonomy and mental attitude presentation. On the other hand, MaSE and ROADMAP are not clear enough to model an agent with high autonomy and intelligent concept. From some practical parameters, i.e. clear notation, ease of learning, ease to use, adaptability, traceability, consistency, and refinement, the three compared methodologies have fulfilled these standard criteria (Al-Hashel, et al., 2007).

As presented in table 3.1, a systematic comparison using conceptual screening matrix provides the quantification of strengths and weaknesses of 3 agent-methodologies. This comparison table shows that Prometheus methodology has more advantages rather than the two other methodologies. The criteria of comparison and the score of justification is followed the comparison table published by Al-Hashel.et al., (2007).

Table 3.1: Comparison of three multi-agent methodologies

SELECTION CRITERIA		**Alternatives**		
		ROADMAP	**MaSe**	**Prometheus**
C1	*Illustrates the scale of the details within each development phase*			
	System specification	+	0	+
	Analysis	+	+	+
	Architectural design	-	+	+
	Detailed design	-	-	+
C2	*Present the measure of agent concept that each methodology support*			
	Autonomy	0	0	+
	Mental attitudes	0	0	+
C3	*Shows the scale of the modeling criteria within each methodology*			
	Clear notation	+	+	+
	Ease of learning	+	+	0
	Ease of use	0	+	0
	Adaptability	+	+	0
	Traceability	+	0	+
	Consistency	0	0	0
	Refinement	0	0	0
	Scalability	0	-	-
	Concept overoad	0	0	-
C4	*Compares the properties of the methodologies*			
	Openness	+	-	0
	Environment	+	0	0
	Abstraction	+	+	+

SELECTION CRITERIA		Alternatives		
		ROADMAP	**MaSe**	**Prometheus**
	Tracebility	+	+	+
	Modeling	0	+	+
	Complexity	-	-	0
	Ease od use	+	+	-
	Liimitations	-	-	+
	Language	-	0	+
	Reusability	+	0	0
C5	*Illustrates the available activities in each development phase*			
	System specification	-	-	+
	Analysis	+	+	+
	Achitectural design	0	0	+
	Detailed design	-	0	+
C6	*The toolkits for development*			
	Scope of development	0	0	+
	Model validation	-	0	+
	Sum +'s	*13*	*11*	*19*
	*Sum **0**'s*	*10*	*14*	*9*
	Sum -'s	*8*	*6*	*3*
	Net score	**5**	**5**	**16**
	Rank	**2**	**2**	**1**

Based on above previous study analysis and the screening matrix, it can be concluded that Prometheus is more capable for presenting the human modeling in evacuation process. Prometheus methodology gets the 1st rank of those three agent methodology comparison and meet the most of the criteria defined by El-Hasel, et al. However, ranking is not the only factor used to determine the best methodology. Type of problem and scope of application should also be considered for deciding the best methodology (Tran, et al., 2005).

3.2. Prometheus Methodology

Prometheus, a methodology to construct multi-agent systems and the detail components of agents (Padgham, et al., 2004), can be classified as a top-down approach for agent development. Prometheus refines the system from the system objective to the detail planning of each agent as systematic hierarchy breakdown. There are three main phases of Prometheus i.e. system specification, architectural design and detailed design (Padgham, et al., 2004). Fig 3.1 shows the detailed phases to apply Prometheus methodology.

Goals definition and components determination of system are the prominent process of system specification phase. In order to achieve the goals of systems, the scenarios are also created in the beginning agent-based modeling. These scenarios are supported by the functionality on the implementation stage. Functionality is a process to refine and grouping some goals in system specification (Padgham, et al., 2005).

In system specification, some agents are created and built with detail interactions on architectural design phase. Dynamic interactions between agents are described with some relevant protocols and also previewed in specified interaction diagrams. The system overview diagram is the most important part of Prometheus methodology and based on that the communication between component of system can be evaluated (Padgham, et al., 2005).

The detailed design phase breaks down the previous phase to develop internal structure of each agent. Some plans build inside the agent to specify the capability and how the agent achieves its functioning within the system. A capability is a modules attached to the agents as a refinery of its functionality. Each detailed design of agent has a process diagram to show the internal processing related to the protocol specification and must consider the data, events and plans related with the agent (Padgham, et al., 2005). Iterative process and inter-connection among components in Prometheus design made the change to one aspect of the system, may affect to other aspects in the systems.

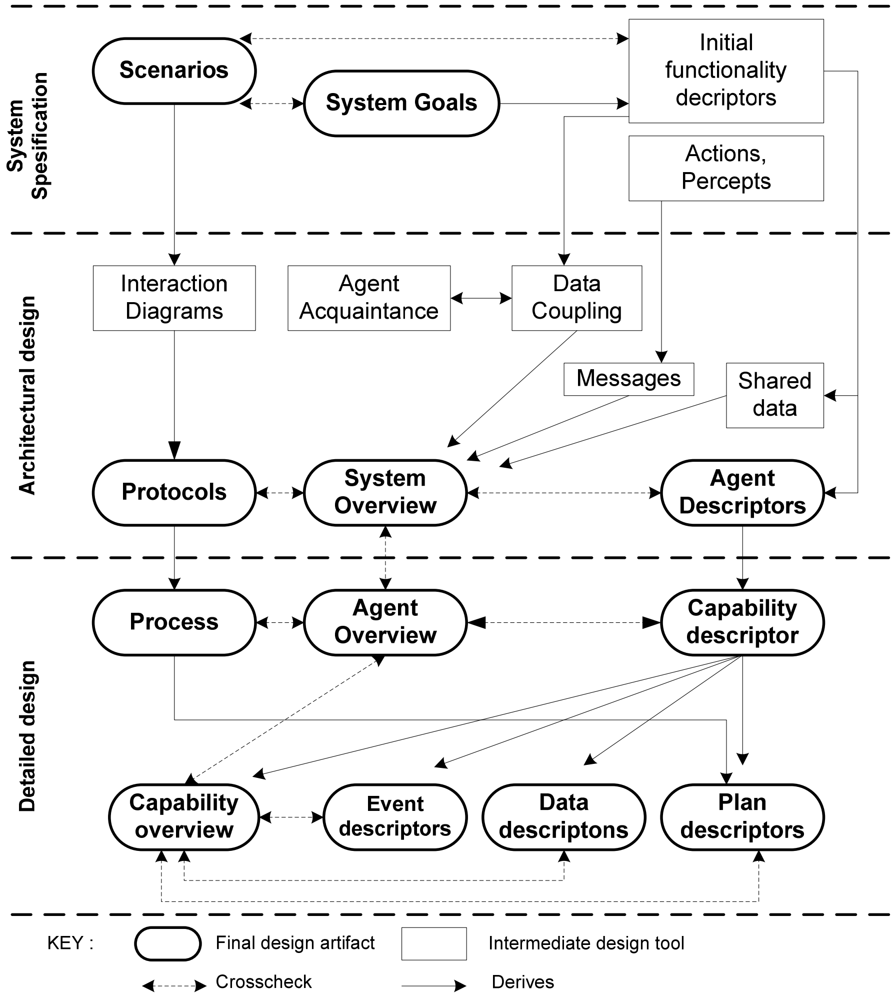


Figure 3.1: The detailed phases of Prometheus methodology **(Padgham, et al., 2004)**

It is important to preview some legends or labels utilize in Prometheus methodology and figure 3.2 shows some legends to present the system components.

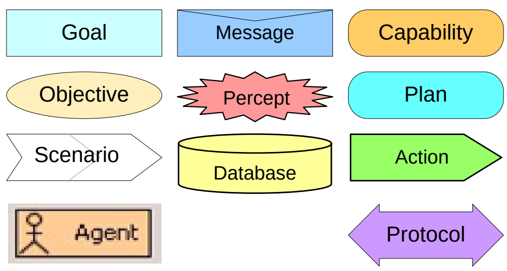


Figure 3.2: Legends used for Prometheus methodology (Padgham, et al., 2004)

3.3. Model Development

Prometheus design tool (PDT) version 3.1 (www.cs.rmit.edu.au/agents/pdt/) has been applied to ensure the development of evacuation system appropriated with Prometheus methodology's role.

Developing agent-based simulation for evacuation process is not just simply simulating the movement of occupant in the fired building. Detailed component of evacuation system must be incorporated with the system objectives and present the characteristic of agent. As stated in previous chapter, two hypotheses will be tested which is mean that the simulation should able to perform some specified experiments. First experiment is studying the response of occupant to the emergency alarm during pre-movement phase and the second experiment is studying the comparison between two methods to get the way out from building in evacuation process. Detailed development phase of Prometheus methodology to construct the evacuation simulation will be described on next sub-chapter.

3.3.1. System Specification

Simulation of emergency evacuation in a multi-level building has some complex aspects to consider. Occupant with his/her unique behavior is difficult aspect to simulate (Pan, et al., 2006). It is necessary to define the specification of evacuation system so that the scopes of study get more focused and directed. Figure 3.3 shows the overview of system specification.

A. Goal Overview

(Gwynne, et al., 1999) has reviewed some evacuation models and simulations and these models have similar objectives to achieve, these are *minimizing TET* (Goal #1) and *maximizing number of safe people* (Goal #2). Even by minimizing TET has a positive correlation to higher number of safe people but it is still necessary to state the goal maximizing number as our concern to evacuate all occupant alive.

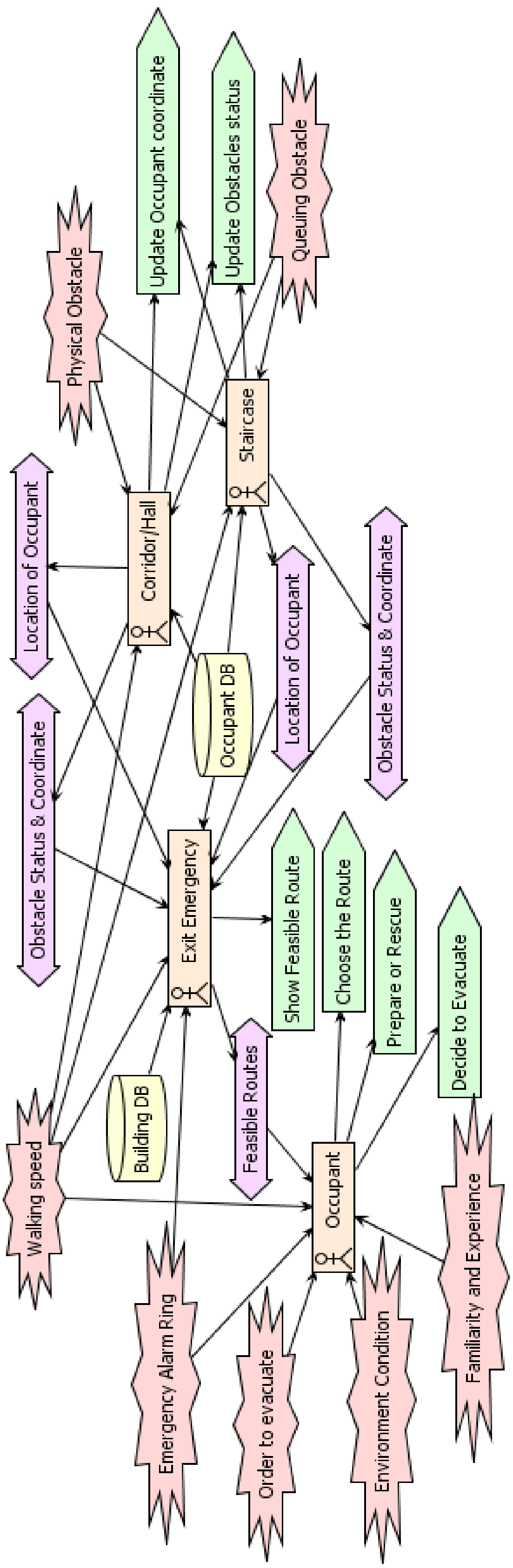


Figure 3.3: Evacuation system overview diagram

There are two potential obstacle could be appeared during evacuation, length of occupant queuing (bottle neck) and physical obstacles i.e. fire and building damage (Rahman, et al., 2007). So, *avoiding the bottleneck* (goal #3) and *avoiding the potential accident* (goal #4) are set as sub-goal to achieve. These two goals can be simplified to the goal *finding an obstacle* (goal #5). It is mean that by finding an obstacle in the building during evacuation, the system will also achieve the goal #1 and goal #2. Detail description of goals statement shows on figure 3.4 as below.

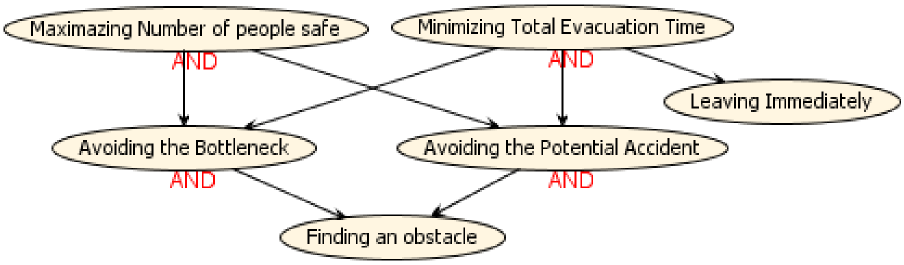


Figure 3.4: Goals statement of simulation

The goal *leaving immediately* (goal #6) is related to pre-movement phase evaluation during evacuation. This goal setting is motivated by ignoring immediate leaving which discussed on chapter 2.

B. Functionalities

Four functionalities are defined to manage and operate the system interaction in order to achieve the goals. Figure 3.5 shows the relation of functionalities, goals and some actions.

Calculate number of people in queue (functionality #1) is a function to control the length of queue and calculate the utilization of building spaces. If the length of queue is over than allowable number then the obstacle status will update to certain conditions such as bottleneck status.

Physical obstacle is also classified as a real obstacle during evacuation. The operation handled by this functionality #2 (identify physical obstacles) is to spot the fire/building damage location in the building in order to avoid the potential accident.

When a physical obstacle has been identified, the obstacle status will updated to certain conditions e.g. route block status.

Determine the feasible route (functionality #3) is an important function to minimize number of safe people by calculating the shortest route. The route determination maintains the goal maximizing number of safe people by considering the potential obstacles in the building.

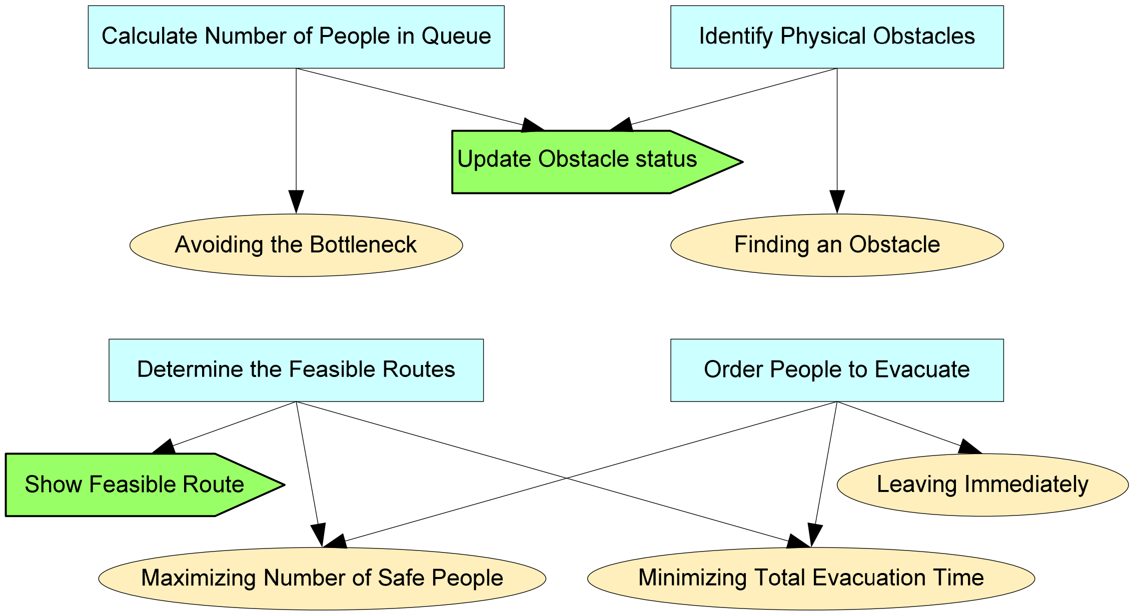


Figure 3.5: Functionalities diagram of simulation

Operating and managing the people response against alarm warning system are the function of order people to evacuate (functionality #4). This function supports to achieve the goal *leaving immediately* since pre-movement phase take significant contribution in consuming TET (Pires, 2005). By providing information to occupants, higher response awareness to leave the building immediately can be achieved.

C. Scenarios

Prometheus methodology provides scenario definition in system specification phase. In order to test two research hypotheses, two scenarios has been built to perform these hypotheses in the simulation. These are, scenario *leaving immediately* to present the behavior study during pre-evacuation phase and scenario *finding an obstacle* to apply proposed methods to get the feasible route determination in movement phase.

First scenario, *leaving immediately*, has been developed to describe some actions is taken by occupant when the emergency alarm ring. This scenario is triggered by emergency alarm and influenced by familiarity of environment or experience of occupant. Once the emergency alarm ring, an action, decide to evacuate, is started which generate a probability number whether he/she will leave the room immediately or just ignore the alarm. When decide to leave is taken, another action , prepare or rescue, is started to generate a probability number whether he/she will leave immediately or safe some valuable items or rescue/order the others to leave. When the occupant leaving the room, the next action, choose the route, is started which also generate a probability number whether he/she will ask/confuse to choose the route or not. Minimizing TET (goal #1) is the goal which is maintained by this scenario.

Second scenario, *finding an obstacle*, provides some actions taken by emergency system when an obstacle appeared in the building. The evacuation system obtains some information from sensors in the building and determines the physical obstacle problem i.e., queuing obstacle, physical obstacle and environment conditions. By applying this scenario, the evacuation system capable to identify the obstacle in the building, determine the most feasible route as an alternative path, and show the route to occupant through emergency exit agent. *Avoiding the bottleneck* (goal #3) and *avoiding potential accident* (goal #4) are goals maintained by this scenario to get the *minimum evacuation time* (goal #1).

3.3.2. Architectural Design

A complex design of multi-agent system specification is developed in architectural design phase. There are 4 agent types involved in architectural design; these are occupant agent, emergency exit agent, staircase agent, and corridor/hall agent. As shown at figure 3.7, interaction between agents is built. Some percepts stimulate the agent to generate agent's capability and perform some actions in the system environment.

As depicted in Figure 3.6, the evacuation system architecture is presented with some input parameters, the simulation engines design, and the output recorder/visualizer. The simulation engines are designed with several capabilities of involved agents in the simulation. This engine is the main part of the simulation to generate each agent behavior and action in the simulation. The detailed description of each capabilities of agent is presented in the detailed design of agent.

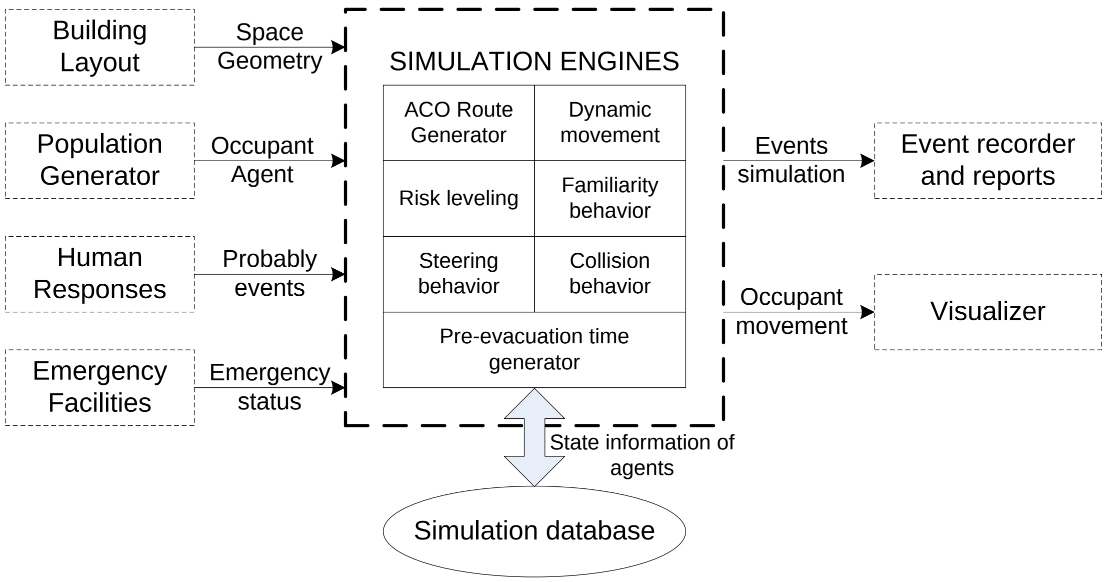


Figure 3.6: Evacuation system architecture with some capabilities of occupant agent, exit sign agent, staircase and corridor agent.

The simulation database is required in the agent simulation to maintain the state information of each agent. Event recorder and reports is a module of the system to capture every simulated event and provide the reports of simulation. Occupant's movement will be presented using the visualizer.

A. Agents

In evacuation process, occupant is the main actor and become the primary object to be safe. Thus occupants are set as agents who capable to response, react, interact and perhaps refuse each other.

Exit sign is known as static building display which has a function to show the evacuation route. Exit sign has been modified to be a smart agent, act like a dynamic exit sign and able to determine the feasible route. The ant colony algorithm embedded in emergency exit agent to calculate the feasible route in real time simulation.

Staircase agent and corridor/hall agentare set to be the supply agent which have a main function to detect and update the obstacle status on every staircase, corridor and hall. The obstacle status is updated by these agents to emergency exit agent through protocol in order to determine the feasible route.

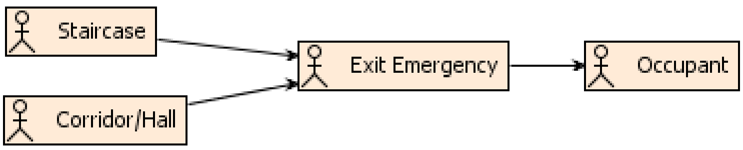


Figure 3.7: Group of agent and Agent acquaintance in evacuation simulation

B. Percept

There are some percept introduce to the evacuation system and describes as follow:

1. Percept #1: *Emergency Alarm Ring*

This percept initiates the emergency conditions in the building. Simulation clock will run once received a signal from this percept. All agents and other component in the system will be activated by this percept stimulation.

2. Percept #2: *Order to Evacuate*

An order to evacuate is received by occupant agent once the alarm ring. The emergency status carried by this percept to occupant agent.

3. Percept #3: *Environment condition*

Occupant reaction and environment situation due to emergency status happened in the building is determined by this percept.

4. Percept #4: *Familiarity & Experience*

Familiarity and experience are the human aspects impress the occupant agent's behavior (Pan, et al., 2006). This percept generates a specific behavior of each occupant agent as reaction against the emergency status.

5. Percept #5: *Physical Obstacle*

Staircase agent and corridor/hall agentare served by this percept to identify the physical obstacle and detailed location.

6. Percept #6: *Queuing Obstacle*

Function and information are delivered by this percept are similar with percept physical obstacle. Calculating the queuing obstacle and its effect in the building is the information provided by this percept.

7. Percept #7: *Walking Speed*

Walking speed of occupant agent is an important variable in movement control. This percepts also useful to specify the location of an agent and to calculate the feasible route. There are 3 types of speed have been specified i.e. slow, fast and very fast.

C. Actions

There are six actions involve into simulation as follow:

1. Action #1: Show Feasible Route

Emergency exit agent performs this action to send and inform the updated feasible route as the output process of “Ant Colony Algorithm” plan. This action immediately shows the direction of feasible route on every exit sign which should be followed by occupant agent.

2. Action #2: Update Occupant Coordinate

This action updates the coordinate of each occupant agent in occupant location DB. Every movement of each occupant agent monitor by corridor/hall agentand staircase agent.

3. Action #3: Update Obstacle Status

When the obstacle appeared, the staircase agent and corridor/hall agent locate and define the obstacle. Once obstacle status has changed subsequently the obstacle DB updated.

4. Action #4: Decide to Evacuate

Occupant agent performs this action as their response to emergency alarm; they may select to leave the building or ignore the warning.

5. Action #5: Prepare or Rescue

Once decide to leave, some of occupants perform preparation time to safe the valuable items or rescue someone else around the building.

6. Action #6: Choose the Route

Choosing an appropriate route may be applied to minimize uncertainty conditions during evacuation. This action is influenced by level of knowledge and familiarity of occupant to the building environment (Pan, et al., 2006).

D. Protocols

Interaction between agents in evacuation planning is a must and some protocols are developed to present inter-agent communication.

Interaction between staircase agent, corridor/hall and emergency exit agent is provided by protocol *physical obstacle status* (protocol #1). As seen in figure 3.8, a message (*obstacle status*) will be updated to emergency exit agent continually. Protocol #2 (*location of occupant*) shows the interaction between staircase agent, agent corridor/hall, and emergency exit agent. A message (*coordinate of each occupant*) provides and updates by staircase agent and agent corridor/hall. Protocol #2 (*location of occupant*) is depicted in figure 3.9.

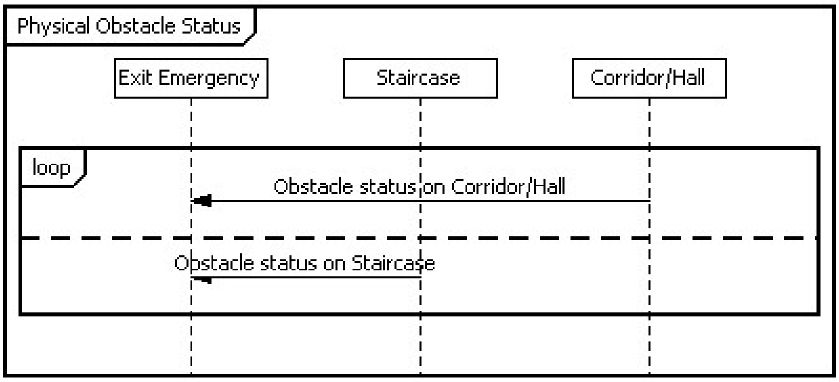


Figure 3.8: Protocol physical obstacle status

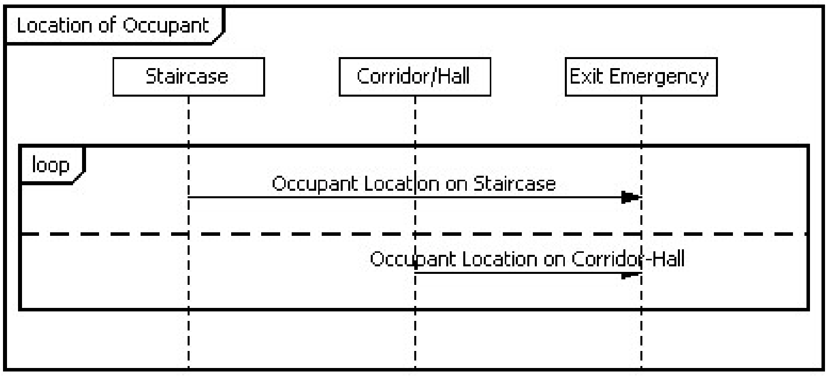


Figure 3.9: Protocol location of occupant

Emergency exit agent and occupant agent are connected by protocol *feasible routes* (protocol #3). In a periodic duration, feasible route (a message) is sent by emergency exit agent to occupant agent. Figure 3.10 shows the interaction inside protocol #3.

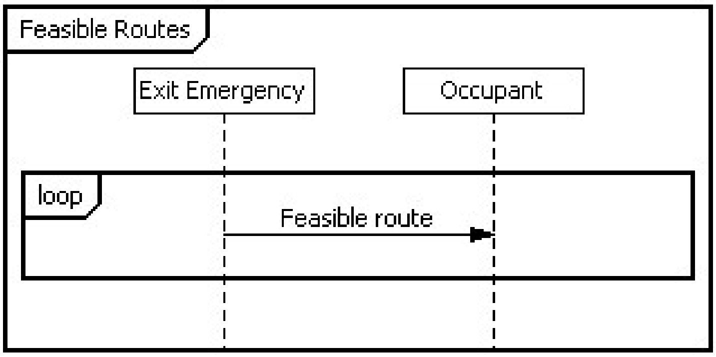


Figure 3.10: Protocol feasible routes

E. Data Coupling

Data coupling shows the process of data transfer in the system. Obstacle DB is written by functionality #1 (calculate number of people in queue) and functionality #2 (identify physical obstacle) and read by functionality #3 (determine the feasible route). This process is an example of input-output processing in the evacuation system.

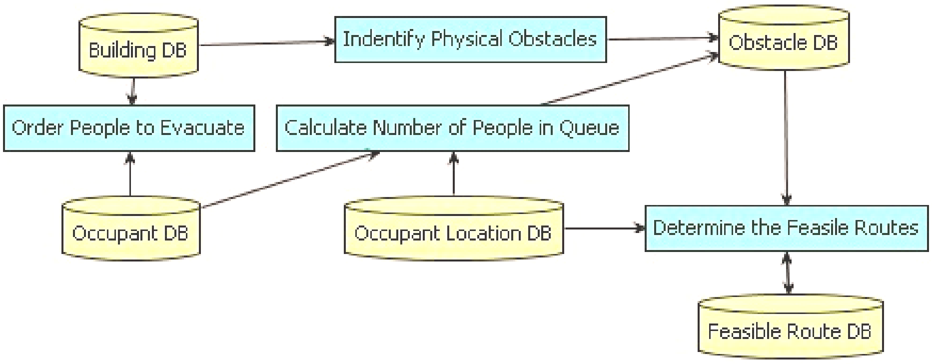


Figure 3.11: Data coupling diagram in evacuation system

As shown in figure 3.11, functionality #1 (*calculate number of people in queue*) and functionality #2 (*identify physical obstacle*) are connected with functionality #3 (*determine the feasible route*) as a group of functionalities. However, functionalities #4 (*order people to evacuate*) have no direct connection with other functionalities.

3.3.3. Detailed Design

Detail structures and components of agent are provided as a part of model development. The interaction diagram shows a process in reaching goal by agent

A. Agent Emergency Exit

Feasible route determination in evacuation planning which performed by emergency exit agent will support reaching main objective of simulation i.e. getting minimum TET. When simulation clock start, this agent receive some information related to location of each occupant and the obstacle from other agent. Occupant DB and building DB has maintained detail occupant data and detailed building layout hence agent emergency exit must be connected to these databases. Detailed input and output process of feasible route determination capability is depicted in figure 3.12.

Feasible route determination as a capability is built with Ant Colony Algorithm inside which able to determine the feasible route by calculating the shortest route and avoiding potential obstacle appeared in the fired building. The feasible route is shown to the occupant agent by sending a message to all exit sign in the building.

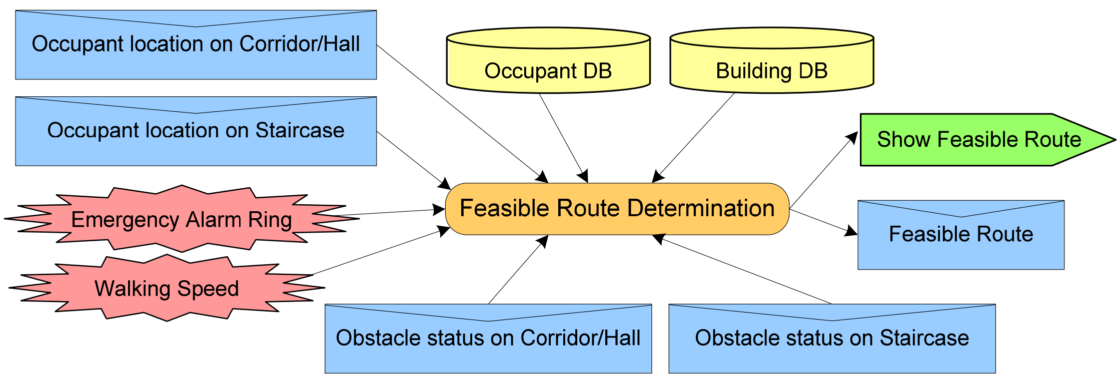


Figure 3.12: Agent emergency exit overview diagram

ACO has been used as a detail plan for 'Feasible Route Determination' capability. This detail plan needs some information to determine the feasible route, such as occupant location, distance to assembly point and building specification. ACO has been modified by adding a physical obstacle factor to probability function (Rahman, et al., 2007). The detailed expansion of ACO is provided in chapter5. Figure 3.13 shows the diagram of 'Ant Colony Algorithm' plan and algorithm 1 provides the detail application codes.

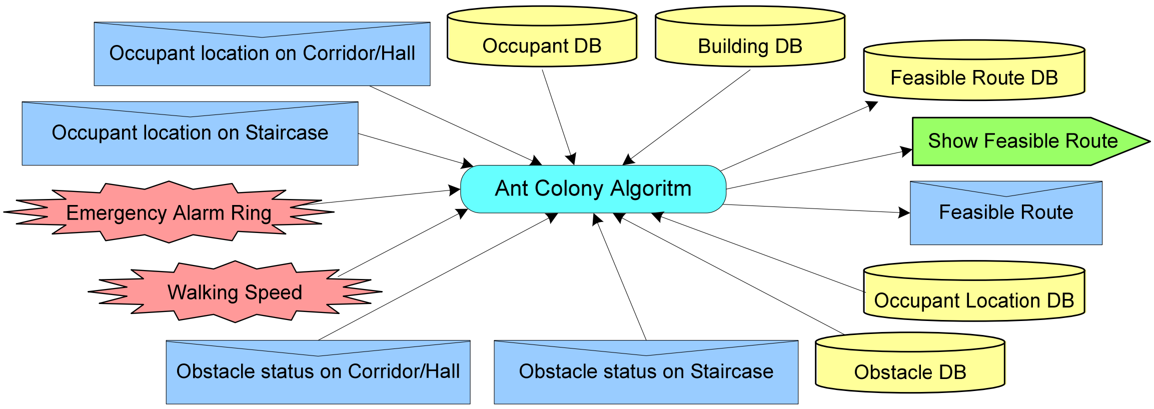


Figure 3.13: Detail description of 'feasible route determination'

```
Algorithm 1: Procedure 'Ant Colony Algorithm'
Connect to Occupant DB
Connect to Building DB
Read initial location of Occupant
Read initial Obstacle status
Read walking speed
Calculate distance between nodes
Set number of cycle
Set number of ants=total number of occupants
Set initial pheromone, i to j
Set initial probability function, i to j
For i=1 to number of occupant
      Place ants to location of occupant
  Set pheromone, i to j
      Update pheromone, i to j
  Update obstacle status
  Calculate probability function, i to j
      Update probability function, i to j
 Choose appropriate value of probability function
  Move ant to next node
      If ant arrive at assembly point then
            Update the distance of trip
            Update number of circle
            If distance of trip = shortest route then
            Set shortest route = distance of trip
            End if
```

```
  End if
Next i
Send feasible route through protocol
```

B. Occupant Agent

As the main actor in simulation, able to response to any changes within the environment is required to present the proactive behavior of occupant agent. Occupant movement control is built inside the *response and move* capability. Figure 3.14 shows the overview diagram of occupant agent.

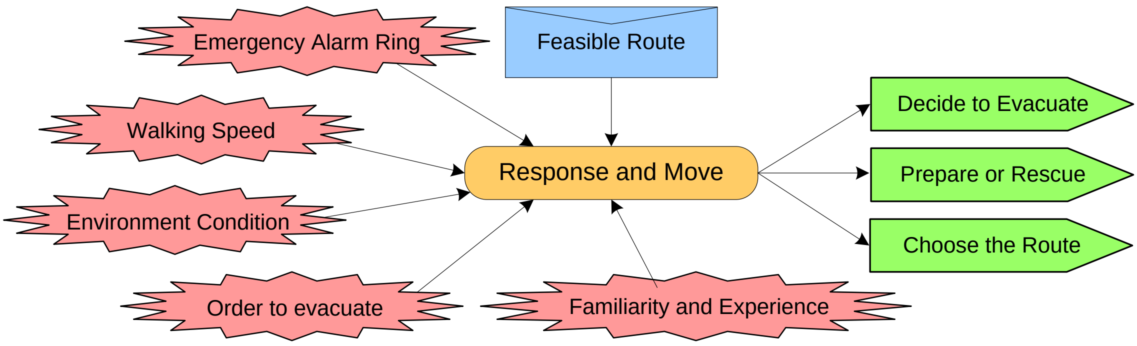


Figure 3.14: Occupant agent overview diagram

And as shown in figure 3.15, capability *response and move* is divided into capability *pre-evacuate response* and capability *movement and interaction*. Roles to determine occupant agent's response by applying certain probabilistic values has built inside capability *pre-evacuate response*. Once the occupant agent decide to evacuate (action #4), capability *movement and interaction* is activated to control occupants movement and provide some roles when the collision happened among the occupant agent.

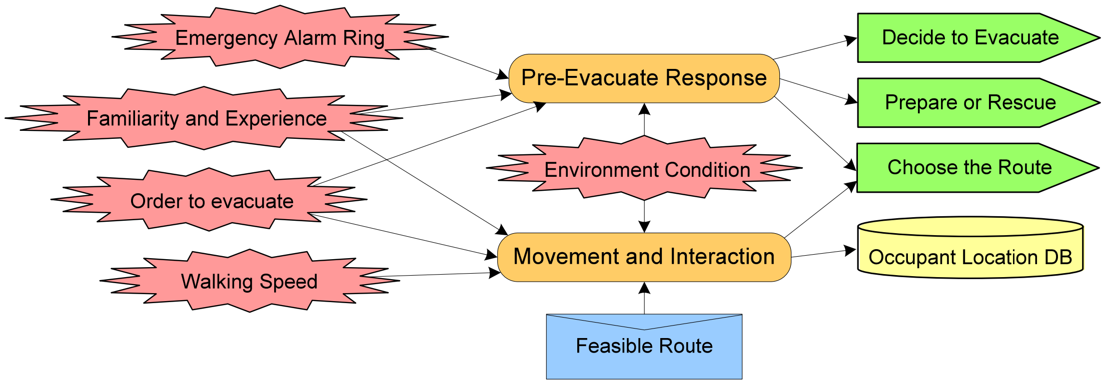


Figure 3.15: Detail description of 'response against emergency alarm'

Refers to Pires (2005), a method to asses human cognitive behavior in evacuation is applied to the system and the Single Value Network (SVN) for start egress motion attached to the simulation. When received emergency status from percept #1 (*emergency alarm ring*) or get an order to evacuate from percept #2 (*order to evacuate*), after t_n second occupant agent would ignore these percept, and the egress not initiated yet. After next t_n second, the occupant agent decide to leave or notified about the emergency, but the occupant agent does not decide to start to egress, another probability to safe something valuable or rescue/order the others is taken. For further t_n second, the occupant agent decides to start egress, but occupant agent does not choose an egress path to take, so the egress is not initiated yet until the route chosen. Figure 3.16 shows the detail description inside *pre-evacuate response* capability. Algorithm 2, 3, and 4 present the detail application code as a part of *pre-evacuate response* capability.

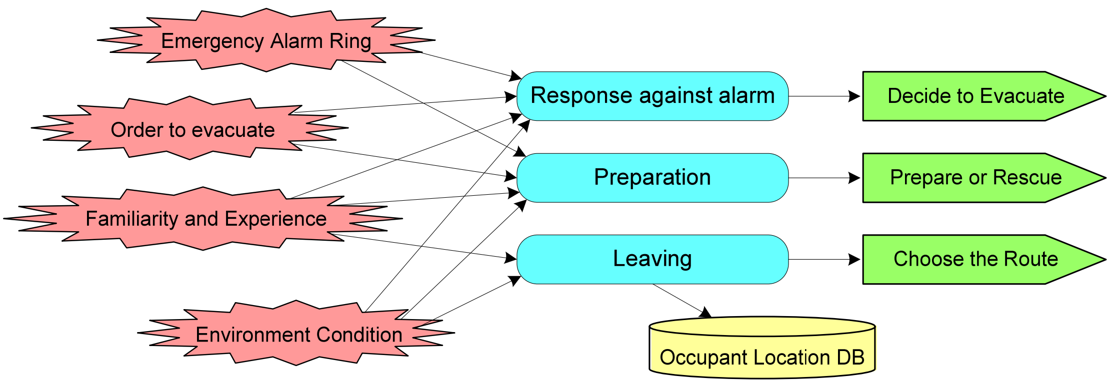


Figure 3.16: Detail description of 'pre-evacuate response'

```
Algorithm 2: Procedure ‘Response against alarm’
On simulation clock: tn
If emergency alarm ring then
Read some percept
Generate response #1 (a probability value)
If response #1 > on leaving probability then
      Decide to leave
      Else
            Ignore the order;
End if;
End if
```

```
Algorithm 3: Procedure ‘Preparation’
On simulation clock: tn
If decide to leave then
Read some percept
Generate response #2 (a probability value)
      If response #2 > on preparing/rescuing probability then
            Prepare or rescue
            Else
                  Evacuate;
      End if;
End if
```

```
Algorithm 4:Procedure ‘Leaving’
On simulation clock: tn
If decide to leave then
Read some percept
Generate response3 (a probability value)
      If response3 > on choosing path probability then
            Prepare or rescue
            Else
                  Evacuate;
      End if;
End if
```

Capability *movement and interaction* determines the occupant movement speed and presents the interaction among the occupants. As presented on chapter 2, (Helbing, et al., 2000) has been defined the acceleration equation for people movement in panic situation. In this thesis, the movement equation is applied to present the panic behavior in the simulation. But some adjustments to the acceleration equation are outlined in order to minimize the number of parameters and exclude the irregular outflows in the simulation.

A simple model simulation to study Helbing’s acceleration equation (2.3) has been applied using Simulink. We simulate an occupant run and will face a wall 100 meter from the original position. The simulation parameters are set based on Helbing,et.al, i.e.: $v_i^0 = 1.8 m/s$, $\tau_i = 0.5 \sec$, d_{iw} = 100m, m_i = 80kg, simulation sampling time (T) = 100second, A_i = 2 10^3 N, B_i = 0.08m, k=1.2 10^5 kgs^{-2}, and $\kappa = 2.4.10^5 kg.m^{-1}.s^{-1}$. Based on the simulation result, the velocity of people's movement is changed too fast since the reasonable maximum velocity performed by human i.e. 1.8 m/s can be achieved on the first second of starting movement. People need very short time to accelerate their movement and achieve desired maximum velocity. Human also able to decelerate their movement when faces any obstacles such as other human or physical building structure. As seen in figure 3.17 as (Helbing, et al., 2000) model result, people reach the maximum velocity and the stationary conditions only in 1 second after the occupant move. When an obstacle appeared 100 meters in front, people only need 1 second to reduce the velocity of movement.

The acceleration model presented by (Helbing, et al., 2000) is not confidence to present a people movement where the desired velocity can be achieved and released in a very short period of time. In this thesis, this model has been adapted with simple definition of acceleration of people movement. In the simulation, people with panic behavior will perform running speed or under nervous conditions with desired velocity equal to 1.8 m/s (Lo, et al., 2002). Occupant under normal or not in panic conditions will have standard walking speed equal to 1 m/s (Helbing, et al., 2000). In the simulation design, occupant with panic conditions reach their desired velocity of movement after 1 meter distance from base position (*v(0)*) and occupant under normal conditions need 2 meters to get their desired velocity. In order to present the interaction between occupants and with the physical building structure, occupant with panic conditions will start to decrease their movement when the position is 1 meters long from the other occupant or wall, and occupant under normal conditions will reduce their velocity of movement 2 meters long from the obstacle. This movement parameter adaption is depicted in figure 3.18.

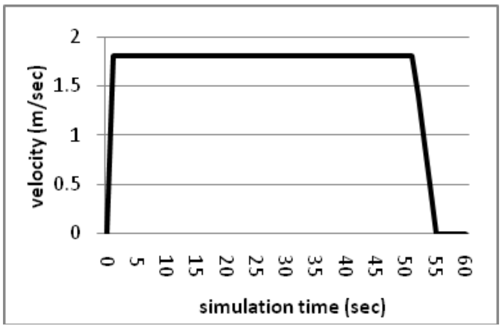


Figure 3.17: Simulation output (Simulink)

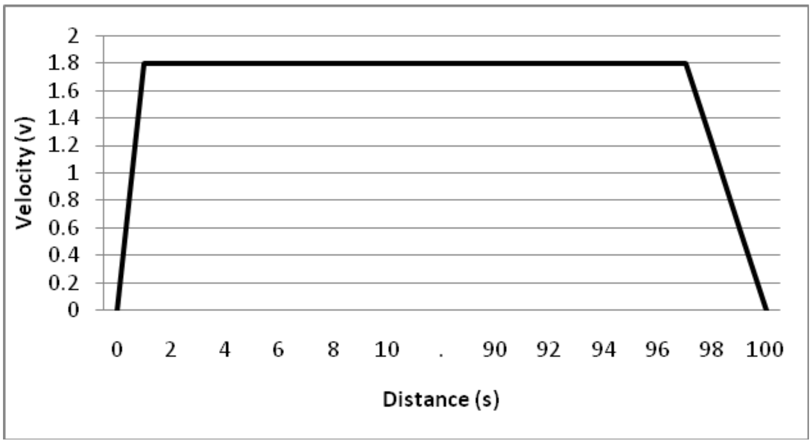


Figure 3.18: Velocity of people movement

C. Staircase Agent

Staircase agent is built with 2 main capabilities which able to identify the coordinate of each occupants on staircase and capable to find out the potential obstacle status on staircase. Determining the occupant detail location coordinate and the obstacle status is important to calculate feasible route in evacuation. On practical application, this capability must be supported by some sensors to monitor people movement and sensors to detect a disaster problem such as: fire or smoke detector. Figure 3.19 shows the detail description of staircase agent.

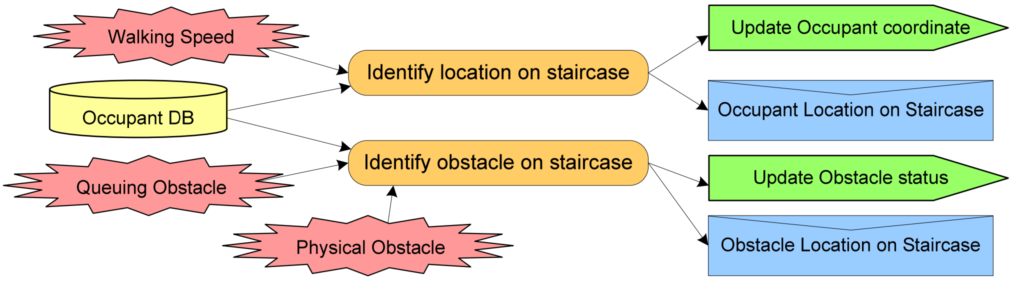


Figure 3.19: Staircase agent overview diagram

Capability of *identify location on staircase* receives percept #7 (*walking speed*) and has a proper connection to *occupant DB*. Figure 3.20 and algorithm 5 present the detail description of *identify location on staircase* capability. By managing a plan, *position and area definition*, the detail coordinate of each occupant can be updated through *occupant location* DB periodically.

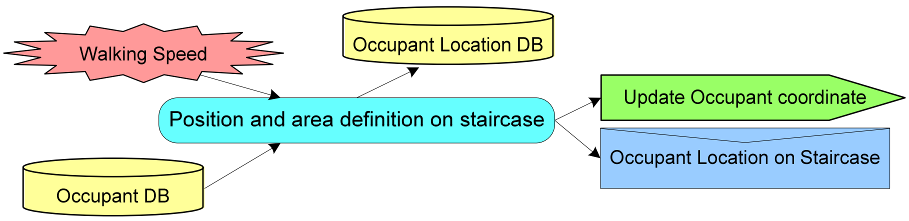


Figure 3.20: Detail description of 'occupant location identification on staircase'

Algorithm 5: Procedure 'Position and area definition on staircase"

```
Read walking speed
Open Occupant DB
If Position X and Position Y on coordinate staircase then
Set area of occupant = area of staircase
Set new Position X
Set new Position Y
Send occupant location to protocol #2
Update occupant coordinate
Update Occupant location DB
End if
```

Capability *identify obstacle on staircase* is described in figure 3.21. Two main inputs, percept#5 (*physical obstacle*) and percept #6 (*queuing obstacle*), is computed by procedure *obstacle determination* to determine the obstacle status.

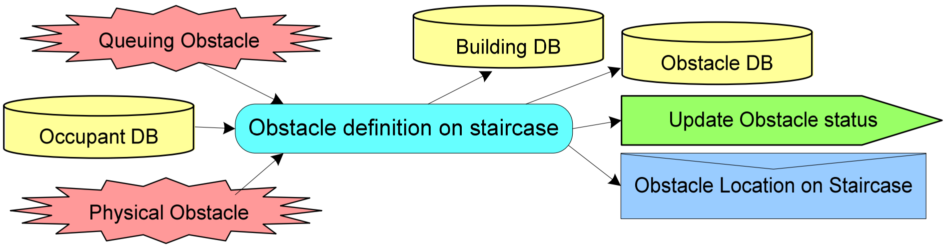


Figure 3.21: Detail description of 'identify obstacle on staircase'

An obstacle in the fired building clearly defined as a risk that must be considered as barrier in evacuation process. From evacuation planning point of view, obstacle itself could be identified as the bottleneck of people queuing, physical barrier caused by building damage or could be a fired object. Accordingly, the capability of staircase agent to *identify an obstacle* is a must to estimate the weight of risk affected by an obstacle. Risk leveling has been defined into three levels as following:

a. **Low risk** (staircase utilization <50%)
b. **Medium risk** (staircase utilization 50% - 75%)
c. **High risk** (staircase utilization > 75% or a physical obstacle appeared on the staircase).

Algorithm 6: Procedure 'Obstacle determination on staircase'

```
Read queuing obstacle
Read physical obstacle
Open occupant DB
Set initial obstacle status on staircase
Select case Number of occupant on staircase
Case < 50% of staircase capacity
Obstacle status on staircase = Low risk
Case 50% - 75% of staircase capacity
Obstacle status on staircase = Medium risk
Case > 75% of staircase capacity
Obstacle status on staircase = High risk
End select
If physical obstacle appeared on staircase then
Obstacle status on staircase = High risk
End if
Send obstacle status to protocol #1
```

```
Update status obstacle
Update building DB
Update obstacle DB
```

D. Agent Corridor/Hall

Corridor/hall agent has similar functions and capabilities as well as staircase agent. Corridor/hall agent measure and monitor each occupant movement on corridor and hall. This agent also able to determine the potential obstacle appeared on corridor and hall. The overview diagram of corridor/hall agent is depicted in figure 3.22.

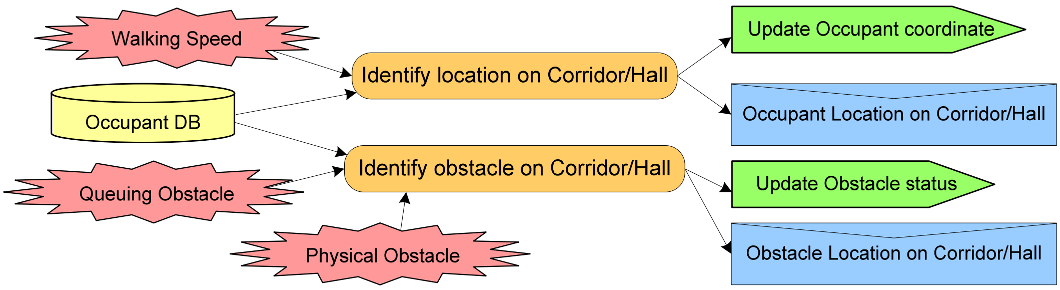


Figure 3.22: Corridor/hall agent overview diagram

3.4. Implementation

Prometheus methodology has applied to construct the emergency evacuation model of simulation and a computer simulation has been developed as the implementation of evacuation model design. The simulation software, namely SEEP 1.5 is built using Visual Basic platform. Next sub-chapter describes the detail inputs and outputs inside the simulation software.

3.4.1. Building Definitions

One of student's hostels in our University has been chosen as a case problem on the simulation. This building has 4 levels of floors, each floor has 4 blocks of rooms, each block has 6 rooms (excluding 1 bathroom and 1 kitchen in every block), and each room has 2 occupants. Figure 3.23 describes the building layout and figure 3.24 provides the detail layout of building.

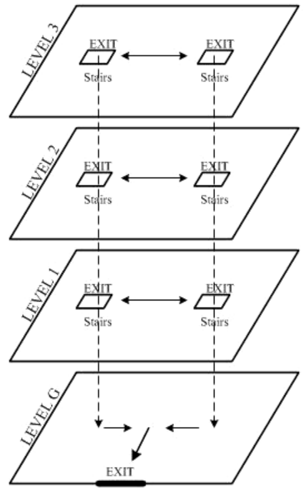


Figure 3.23: Hostel schematic, exits and staircases position

In order to simulate the evacuation process and identify available routes in the building, a network model (Taha, 2003) presenting the route is presented in figure 3.25. Starting point of each block presents by one node on the network. Node 1 represent room at block 1 level 3, node 2 at block 2 level 3, node 5 for block 3 level 3, and node 6 for block 4 level 3. Node 32 represents the exit door on ground floor and node 33 represents assembly point as the end point of evacuation.

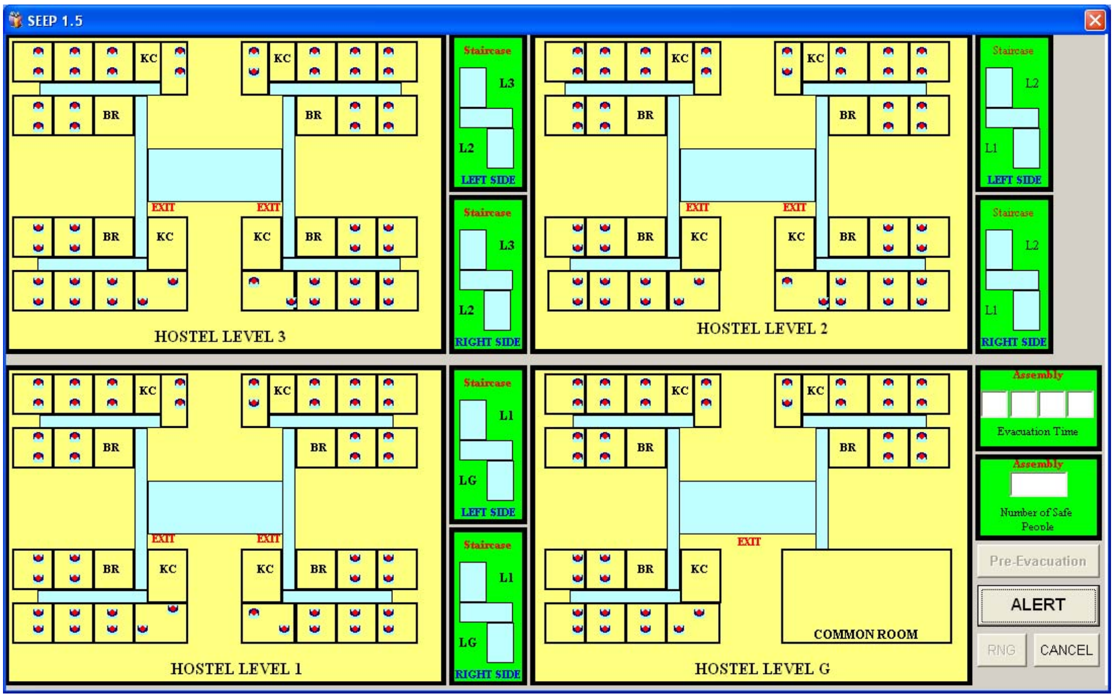


Figure 3.24: Hostel's detail layout (KC: Kitchen, BR: Bathroom, R3.1.1: room number)

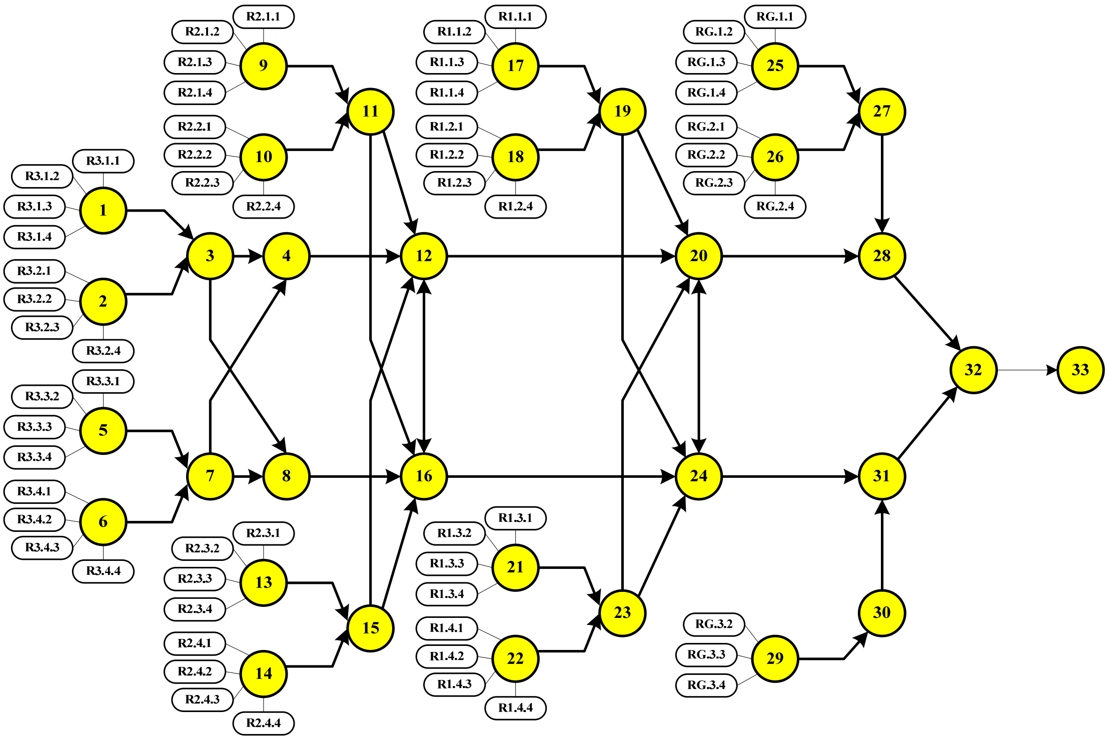


Figure 3.25: Network model of 4 levels building's route definition

3.4.2. Simulation Setup

In this simulation, each people is defined as male with 160 cm average high and walking speed of 1.8 m/s. The average body size is 0.5m x 0.5m (a square).

The drawing scale to present the building layout is 1:200 meters. Average room dimension is 3 m x 3 m, corridor width is 1.5 m, and staircase width is 2 m. Capacity for preparation area on corridor/hall per each level is 25 occupants and capacity for preparation area on each staircase is 20 occupants. These capacities can be modified manually though the input parameter setting, as seen in figure 3.26.

Some physical attributes can be adjusted by modifying some input provided to SEEP 1.5. Maximum number of occupants involve is 180 occupants and this number presents the actual number of occupant in student hostel. There are three types of simulation speed i.e. slow, fast and very fast. SEEP 1.5 also provides overtaking behavior option in simulation; it is allowed to enable overtaking option or set for queuing behavior or disable the overtaking option.

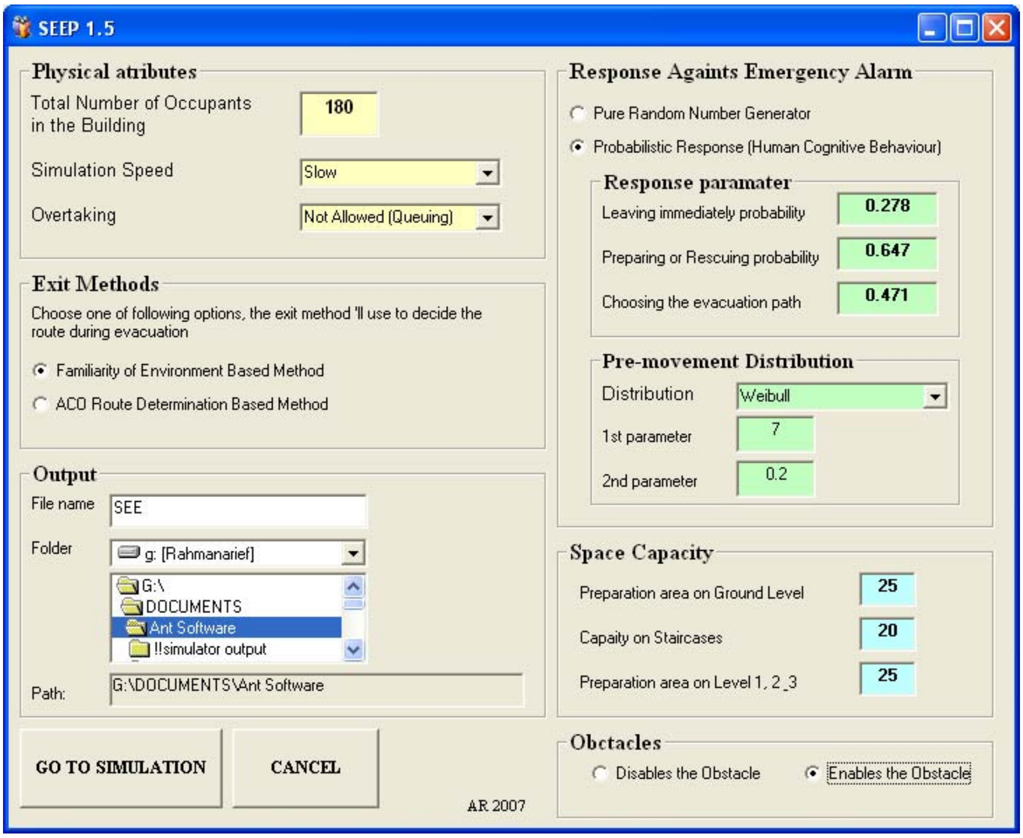


Figure 3.26: Simulation input parameters for SEEP 1.5

The time generation setting can be modified by user following specific time distribution. SEEP 1.5 provide two types of time distribution i.e., exponential distribution and weibull distribution. Default value of distribution parameters has already set by SEEP 1.5 for each distribution and another input of value is allowed.

In order to apply some scenarios related with research hypotheses, SEEP 1.5 provides exit methods option and response against alarm option. There are two options for way finding methods, i.e. familiarity of environment based method or ACO route determination based method. By applying this option, an experiment to compare the performance of two different methods to get the way out is possible to run. Pre-evacuation phase also enable to study by choosing response against alarm option. Human cognitive behavior model is applied to study the response of occupant against alarm notification and this model describe in detail on chapter 4. SEEP 1.5 provides 3 specific actions for cognitive behavior model application with some default probabilistic values based on survey result. Pure random number generator is an option to generate the occupant response time to evacuate which is follow Visual basic's random number generator as normal distribution number generator. For detail description of SEEP 1.5, appendix 1 provide detailed codes, algorithm and some snapshoot figures from the simulation.

3.4.3. Simulation Output

SEEP 1.5 as a computer simulation has built in with some logical procedure and specified algorithm to create several agents in evacuation process. Four levels of building have been presented in one simple window to show the movement of occupants during evacuation process. As seen in figure 3.27, an occupant move from initial position to achieve the assembly point at level G (ground) through corridor/hall and staircase.

Figure 3.27: Simulation preview of SEEP 1.5

SEEP 1.5 provides some reports as the simulation output. From simulation report, it is possible to preview the proportion time of pre-evacuation activities and also enable user to evaluate the simulation performance through number of safe people chart. The utilization of each space in the building can be monitored and evaluated using space utilities report. This computer simulation also serves a report to summarize the performance of experiment including the crowded level. Time consumption calculation for each evacuation phases has provided evacuation time proportion report. Furthermore, detail performance for each occupant in evacuation process can be analyzed through the text file report (.txt). Figure 3.28 shows the captured SEEP 1.5 reports.

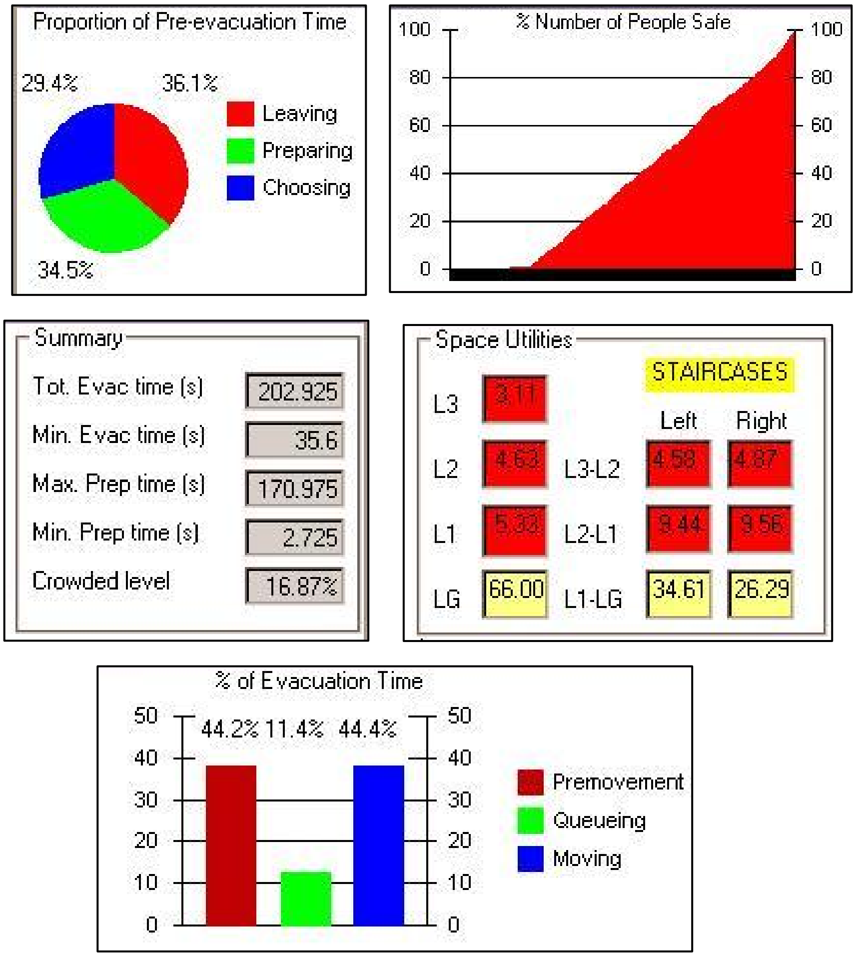
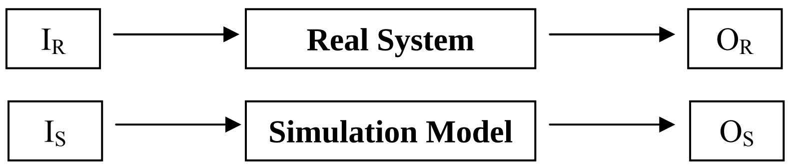


Figure 3.28: Simulation reports of SEEP 1.5

3.4.4. Validations

Simulation model mean to present the real world problem into conceptual model. For that matter, it is important to validate the model to ensure that model has sufficiently accurate for understanding the reality (Stewart, 2003). In this thesis, SEEP 1.5 is validated by black-box validation process where actual walking time has compared with walking time produced by simulator. The comparison between SEEP 1.5 with existing simulation model, EVACNET 4, has done as our second validation process. Model validation concept is depicted in figure 3.29.

Actual walking in normal conditions was measured involved 25 occupants. It was taken from level 3, block 1 and room no 1 (R2.1.1) to assembly point at the ground floor. Average actual walking time is 54.7 second. Simulation has been applied with SEEP 1.5 to get walking time data with same start and end point as actual walking time measurement. Average walking time formed by simulation is 53 second for 25 times runs. T-test (paired to sample for means) has applied to compare the actual walking time with the simulated walking time and table 3.2 shows the t-test result.



I_R: Inputs to real system O_R: Outputs from real system

I_S: Inputs to real system O_S: Outputs from real system

$$\mathbf{H_1: If\ I_S=I_R\ then\ O_S \approx O_R}$$

Figure 3.29: Model validation with the real system **(Stewart, 2003)**

It can be interpreted that both walking time has no significant different since t_{stat} smaller than $t_{critical.}$ It mean than the walking time produced by the simulation sufficiently accurate to represent the real walking time in normal conditions.

Furthermore, in order to get good validation process, model comparison has been applied between SEEP 1.5 and EVACNET 4. EVACNET is a computer program for modeling building evacuations with network model description. Simulation only took the ground floor of hostel building where 48 occupants are involved.

Table 3.2: T-test for actual duration versus simulation output

	Simulator	*Actual*
Mean	53	54.7
Variance	7	1.81
Pearson Correlation	-0.58997144	
Hypothesized Mean Difference	0	
df	10	
t Stat	**-1.56317145**	
P(T<=t) one-tail	**0.074538609**	
t Critical one-tail	**1.812461102**	

Only the ground floor of hostel has been simulated and this floor can be represented the simulation validation process. EVACNET has been developed since 1998 and has been referred by many simulators as benchmark or comparison model. As shows in figure 3.30, an EVACNET network diagram is built to simulate the hostel ground floor. Detailed EVACNET parameter can be found in appendix B. TET produced by EVACNET 4 is 105 seconds. Average evacuation time for hostel ground floor evacuation provided by SEEP 1.5 is 103.51 seconds.

Since t_{stat} smaller than $t_{critical}$, the hypothesis null can be accepted as the t-test conclusion. Table 3.3 previews the detailed t-test output. Hypothesis null present the TET of SEEP 1.5 and TET of EVACNET 4 are not different significantly. SEEP 1.5 has performed the simulation process as well as EVACNET 4 has been provided with the same object/input.

Table 3.3: T-test for TET of SEEP 1.5 versus EVACNET

	SEEP 1.5	*EVACNET*
Mean	103.509	105
Variance	18.03598842	0
Observations	20	20
Hypothesized Mean Difference	0	
df	19	
t Stat	**-1.570083203**	
P(T<=t) one-tail	**0.066450015**	
t Critical one-tail	**1.729132792**	

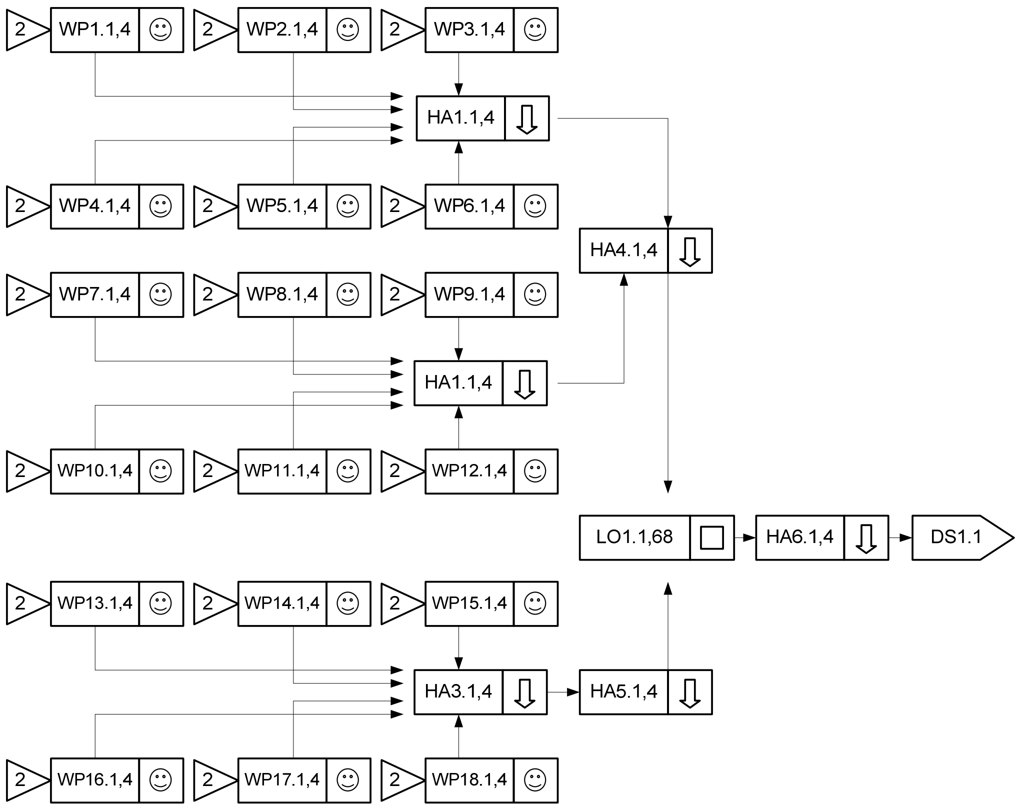


Figure 3.30: Evacnet network diagram for hostel ground floor

3.5. Summary

Detail description of evacuation model development using Prometheus methodology has been provided in this chapter. The complete flow process and structure of Prometheus methodology is presented in this chapter. Evacuation model development and system breakdown are described with some figures and charts. There are three main phases presented in model development, i.e.: system specification, architectural design, and detailed agent.

In implementation part, simulation setup for hostel evacuation and some simulation outputs is presented. The simulator, SEEP 1.5, has passed the validation process. There are two validations are presented in this thesis, i.e. validation with real system and comparison with existing simulation model.

In the next chapter, human behavior modeling in evacuation process is provided and pre-evacuation analysis can be seen in the next chapter.

CHAPTER FOUR: SIMULATING HUMAN COGNITIVE BEHAVIOR IN PRE-EVACUATION PLANNING

Evacuation time encompass to start, time to queue and time to move. As stated in previous chapters, time to start is an important phase to explore since some behavior before leaving has been identified as the causes of high TET consumption. In order to study the influence of some behaviors in pre-evacuation process towards time consumption of TET, a simulation involving some agents were carried out using human cognitive behavior model. The simulation results are presented in this chapter.

4.1. Previous works on Pre-Evacuation Process

This section presents the importance of pre-evacuation phase as a part of evacuation process. Previous studies related to the pre-evacuation observations are presented as the background of our further research.

In any building, emergency status will be identified when some cues are detected by the emergency system and automatically the evacuation process in the building is begun. Once an emergency situation has been declared, all building occupants have to evacuate immediately and leave the building by following the standard evacuation procedure (www.OSHA.gov), e.g.: walking by following the exit sign through staircases. This standard procedure must be implemented in all public buildings.

Some previous studies present a similar conclusion about human response against emergency notification by alarm or safety officer in the building. These response behaviors, such as ignoring the alarm and deciding not to evacuate immediately, have a significant contribution to the delay of the evacuation time. The delay in evacuation process is also affected by some preparation actions before leaving, such as gathering of valuable items, getting dressed, checking the corridor, etc.

As presented in figure 4.1, (Proulx, 1995) has studied the distribution of occupants based on their decision to leave from the building. It shows that some occupants decided to leave immediately but the rest of the occupant took several minutes to get convinced and preparation before leaving took an extra few minutes. Proulx (1995) also conducted some interviews on some occupants and some interview results showed that occupants still need to perform preparation action upon hearing the emergency alarm. It has been reported that many occupants in building 2 and building 3 did not hear any notification from the emergency alarm during the evacuation drill. Only 53% of occupants in building 2 and 44% of occupants in building 3 decided to evacuate for the first 5 minutes. This fact shows that technical malfunction of some building facilities and also a contributing factor to the delay in an evacuation process.

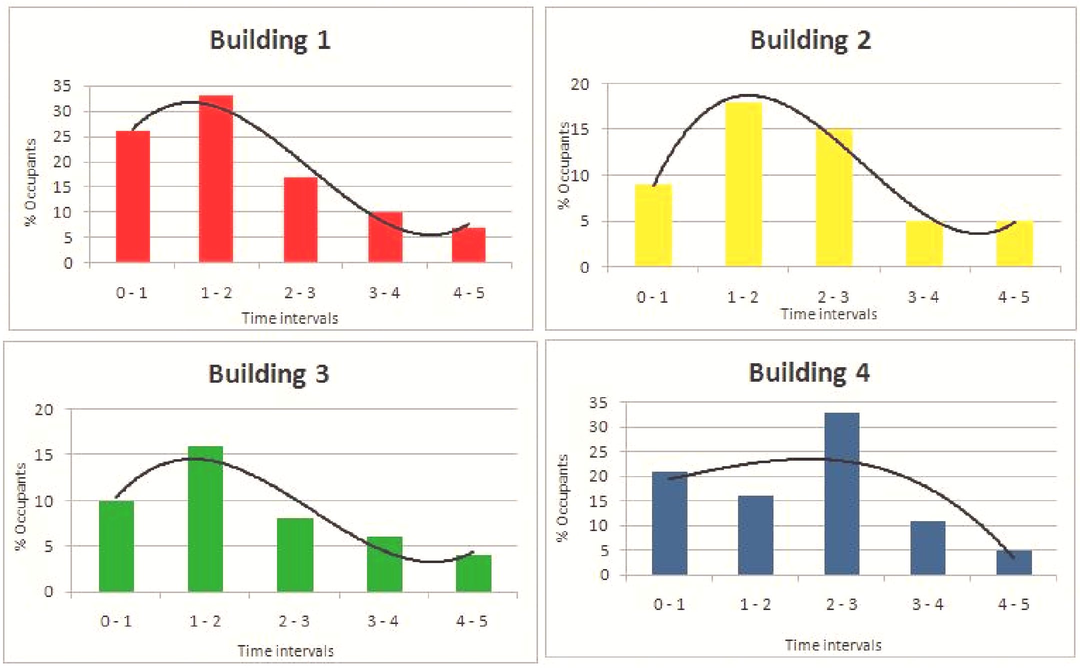


Figure 4.1: Occupant distribution for time to start (first 5 minutes) based on **(Proulx, 1995)**’s experiment.

Summarizing from Proulx's experiment, time distribution of evacuation process is divided into time to start and time to move. Figure 4.2 shows that time to start consume a large part of evacuation time. It takes around 75% of evacuation time in every single experimental building. This fact shows that the pre-evacuation process must be considered as a significant process in evacuation planning. But it is also important to highlight that the time proportion provided by Proulx's experiment might have a different overview compared with different objects or buildings. The evacuation time may also depend on the size of the building, number of occupant and the relative distance to assembly point.

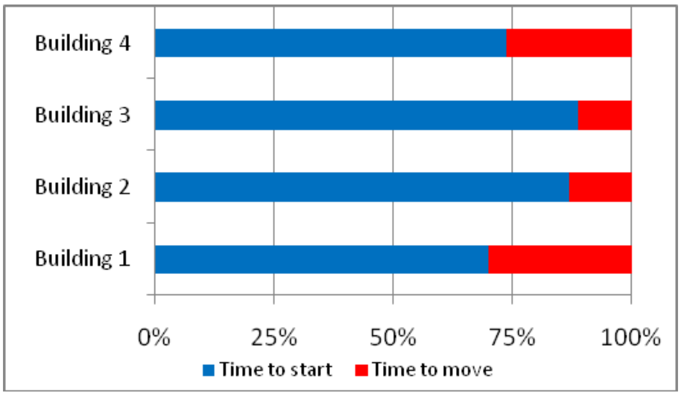


Figure 4.2: Evacuation time with detail proportion of time to start and time to move based on the experiment by Proulx (1995)

Based on the above analysis, it is clear that an evacuation model must consider the time consumption in pre-evacuation phase. A computer simulation designed to represent evacuation process cannot refuse to model the time people take during pre-evacuation phase. Nevertheless, some of the existing computer simulations generate a pre-evacuation time with simple time generation i.e., random number generator. However, some of the computer simulations are not equipped with pre-evacuation time generation. (Pires, 2005) has introduced a model capable of assigning probability value to some probabilistic actions that will be taken by occupants in evacuation planning. The next sub-chapter presents the results of time consumptions study in evacuation planning after applying the human cognitive behavior model.

4.2. Pre-evacuation Survey

An evacuation survey has been conducted to get some responses in pre-evacuation phase. Some questionnaires were distributed to several occupants who worked in 12 different high-rise buildings in Indonesia and Malaysia. Five buildings have 1 to 10 levels of floor and 7 buildings have 11 – 31 levels of floor. One of the objectives of the survey is to study the occupant's response and experience during pre-evacuation period of an emergency situation.

Most of the survey respondents reported of hearing the emergency alarm due to various incidents. The frequency of occurrence of the incidents that triggered the emergency status is reported as in figure 4.3. Earthquake and evacuation drills are the two most frequent causes of the emergence alarm, each constituting 30%. While 25% are made by nuisance alarm. A nuisance (false) alarm perception indicates that the occupant's trust level in the emergency warning system is low. Thus, it is important to study the nuisance alarm perception as an influencing factor on time consumption in pre-evacuation planning. The reliability and accuracy of the emergency warning system in the building can be correlated with the occurrence of nuisance alarm. Other identified incidents that could triggered an emergency starts are fire (10%) and bomb treats (5%).

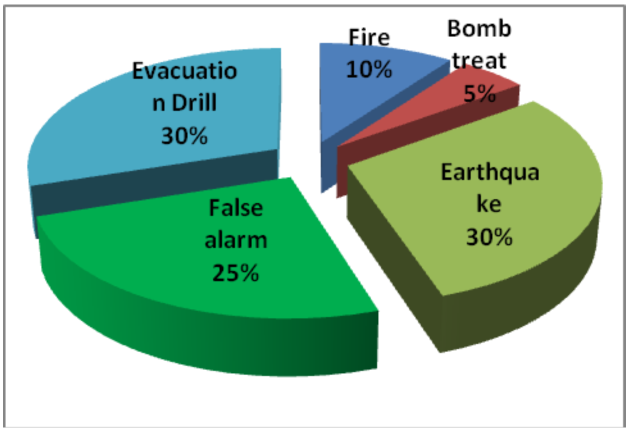


Figure 4.3: Triggered events of emergency status

The survey also included a study on some human behaviors in response to emergency notification. The survey results show that generally occupants assimilate some information and cues related to the emergency situation. Based on the survey, only 15% of respondents get panic upon hearing the emergency notification. Table 4.1 lists some first actions taken by occupants in an emergency situation. It shows that 39% of respondents will run immediately to evacuate once they heard the emergency alarm. But another 28% need a confirmation of the real situation in the building by calling the reception or safety officer. These 2 facts show that emergency alert is not always perceived as valid information by some occupants in the building.

About 22% of occupants feel the need to save personal belongings such as valuable items and the other important or confidential documents. This behavior was also observed by Proulx, who termed theses actions as pre-evacuation actions.

Table 4.1: Survey results showing various first actions upon hearing emergency notifications.

Run immediately to emergency exit	**39%**
Call the reception or anybody to verify the situation	**28%**
Save my own valuable items (i.e., money)	**11%**
Save important and confidential files, data or documents	**11%**
Order/notify someone or others to evacuate immediately	**6%**
Ignore the alarm, it's just a nuisance(false) alarm, I'm busy	**6%**
Take the valuable items or devices belong to company	**0%**

Saving important or confidential documents and valuable personal belongings is given the highest priority by respondents. The weightage of these two preparation actions totaled to 53%. This indicates that saving of important and valuable belongings must be considered in the emergency planning. Some respondents provide a weightage of 17% for action to call the building reception or safety officer to obtain confirmation of the emergency situation. Some respondents consider saving company properties is also important and a weightage of 14% is given to this action. Asking for the evacuation route is considered as the least important in the preparation action, as a weightage of only 3% is assigned to this action.

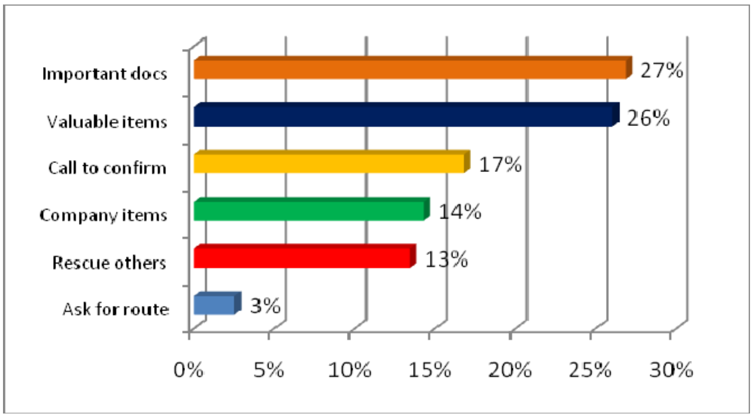


Figure 4.4: Weightage for some preparation actions before leaving

4.3. Human Cognitive Behavior Model

Pires (2005) has designed a framework model to describe human cognitive behavior during pre-evacuation process. A logic diagram as a SVN for start of egress motion analysis is introduced to represent some probability actions taken by occupants during pre-evacuation phase. There are three possible actions that would be taken by an occupant when an emergency alarm rings before he/she decides to evacuate. These are *on* (recognizing the emergency conditions), *se* (starting egress), cp (investigate a path to take). Figure 4.5 presents the SVN for start of egress analysis.

When the emergency alarm rings or some cues indicating the presence of a disaster appear, some occupants would evaluate the real situation inside the building while some occupants would evacuate immediately. However, ignoring the emergency alarm is quite a common behavior among the occupants, especially if the alarm is perceived as a nuisance alarm. As depicted in figure 4.5, Pires labeled this action as on, which represent the process to recognize and analyze some percept received during pre-evacuation phase.

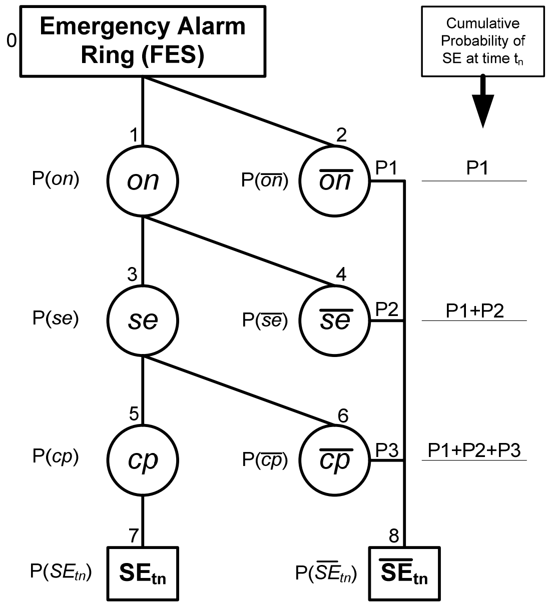


Figure 4.5: Logic diagram for start value networks in pre-evacuation (Pires, 2005)

After t_n second, the occupant who notified the emergency conditions would undertake some preparation actions before starting to egress (SE). This event, preparation actions before leaving, is labeled as *se*. Gathering valuables items, finding children or pet, getting dressed, rescuing/notifying the others before leaving are some examples of *se* given by (Pires, 2005).

The next most probable action that will be taken by occupants is to select the way of egress or evacuation route. Familiarity of the building environment is the most important factor that would influence on the choice of exit from the building. Most occupants with good knowledge of the building layout, e.g. the occupant of the office building, are able to determine the evacuation route rather than occupants with less knowledge of the building environment, e.g. the visitor of shopping mall, museum, or sport stadium. This action of choosing the evacuation route termed as choosing the path (*cp*) must be considered as a time consuming activity and need to be minimized.

The start of the emergency situation is presented by node 0, decision to evacuate is presented by node 7, and node 8 for decision not to evacuate. After t_n seconds, if the occupants decide not to evacuate immediately upon hearing the emergency alarm or any cue, path **0 – 2 – 8** will describe this event. While event *on* is taken after next t_n seconds, but if the action start to egress has not been taken, path **0 – 1 – 4 – 8** will describe this event. The preparation before leaving or any other important action that needs to be done before leaving will take some times and path **0 – 1 – 3 – 6 – 8** describes the *se* actions. Path **0 – 1 – 3 – 5 – 7** means that the occupant has decided to leave the building and has identified the evacuation route.

4.4. Pre-Evacuation Process and Time Consumption

From the survey, some undertaken possible actions by occupants upon hearing the emergency alarm notification have been identified as discussed in the previous chapter. On the SVN model, these 3 possible actions i.e. recognize the emergency condition, start egress, and investigate a path to take are redefined as *decision to leave, preparing the valuable items and choosing the evacuation route*. Table 4.2 presents the probability value of pre-evacuation actions based on the survey results.

Table 4. 2: Probability of pre-evacuation actions

Decision to leave	**0.278**
Preparing the valuable items	**0.647**
Choosing the evacuation route	**0.471**

SEEP 1.5 has been developed with the capability to perform pre-evacuation analysis and a SVN model has been embedded in the simulator. The function of SVN model is to generate the time of pre-evacuation actions. By applying a random number generator (Visual Basic's RNG), the probability numbers are generated with specified probability distributions. Exponential distribution (β=0.4) and Weibull distribution (α=7 and β=0.25) were selected as the probability distribution and were used to determine the probability number of each occupant in the SVN model.

Simulation results show the detail time consumption per each activity in the pre-evacuation phase. For each different probability distribution, the number of replication is 10 running simulations. Figure 4.6 shows the detail pre-evacuation time consumption of each occupant and it can be observed that the area of decision to leave is larger than the others.

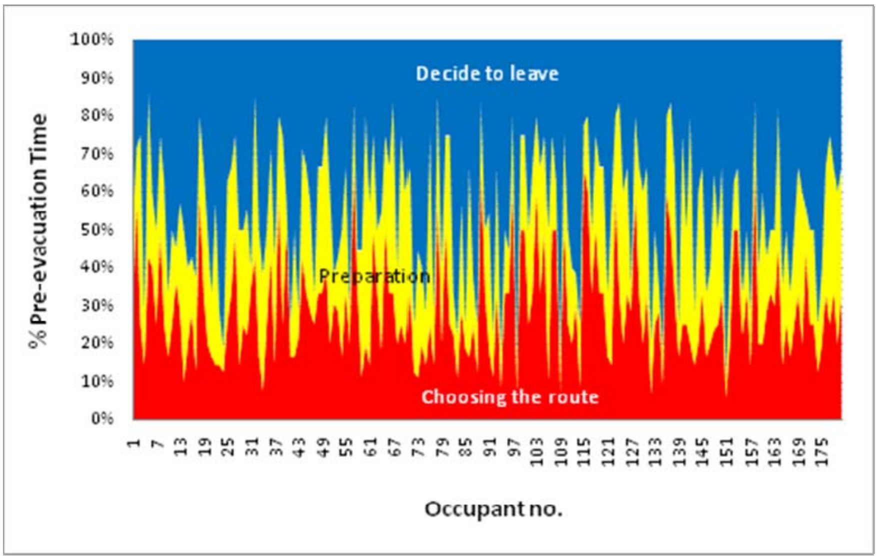
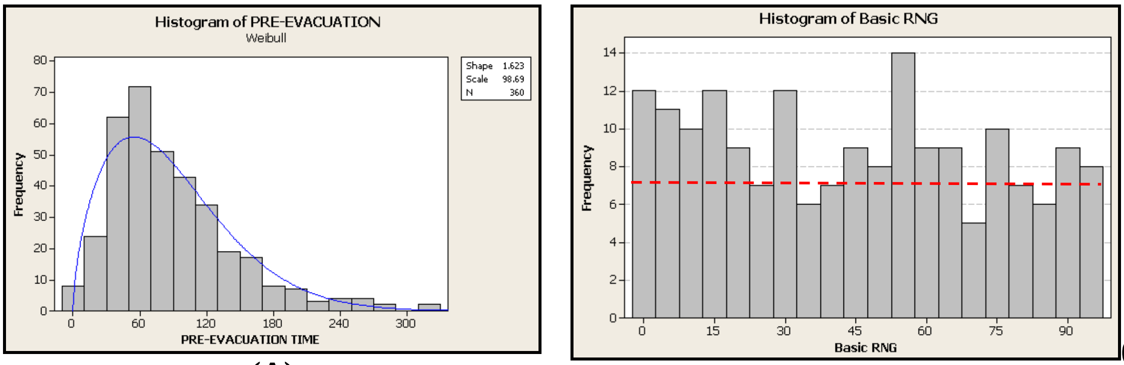


Figure 4.6: Spread of detail pre-evacuation time

Pre-evacuation phase consumed a significant portion of TET and reaches greater than 50% of TET in the most cases. In the simulation, the probability distribution may influence the pre-evacuation time generation. For the exponential distribution, TET reaches 342.8 second (taken from 1 running simulation) and for the Weibull distribution, the TET is shortened to 215.6 second. This shows that the probability distribution on SVN will determine the spread of pre-evacuation time generation.

As depicted in figure 4.7(A), the pre-evacuation time tend to be skewed because some occupants tend to take a longer time to response compared to other occupants. In the case of hostel evacuation, the pre-evacuation time is in good fit with the Weibull distribution. The majority of occupants decided to leave before 120 seconds and only few took a longer pre-evacuation time. This distribution result is quite different from the result of Purser, et al., 2001), which presented a good fit of pre-evacuation time with Log normal distribution. In our distribution test, Weibull presents a higher correlation value (0.958) than Log normal correlation (0.910). The fitting of the distribution curves are different too. However, both Weibull and Log normal are can be used to represent the pre-evacuation time (Stewart, 2003).

The pre-evacuation time can be generated from the random number generator (RNG) function e.g.: rnd() in Visual Basic or rand() in Microsoft Excel. The pre-evacuation distribution time is depicted on figure 4.7 (B). It is observed that the spread of the pre-evacuation time generated by the simple RNG function tends to fit with the Uniform distribution. From the comparison of figure 4.7 (A) and (B), it can be interpreted that the pre-evacuation time generated by the SVN model seems more realistic than the RNG function.



(A) (B)

Figure 4.7: Distribution of pre-evacuation times

Figure 4.8 presents the three components of time that form the TET. On average, time taken to prepare or pre-evacuation time reaches more than 50% of TET. Time to move takes around 40% of TET and time to queue only takes around 10% of TET. This simulation result shows a similar characteristic of time consumption to the experimental result by Proulx (1995). From the experiment, Proulx identified that pre-evacuation phase consumes a large part of evacuation time. Pre-evacuation phase took 75% of TET.

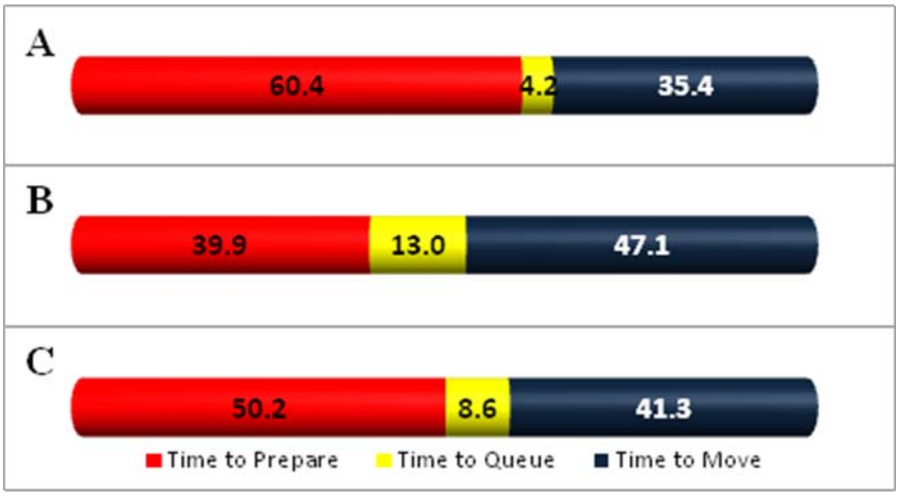


Figure 4.8: Proportion of evacuation time. (A) Evacuation time with Exponential distribution on SVN; (B) evacuation time with Weibull distribution on SVN; (C) average evacuation time.

Even though the queuing process takes only a small portion of TET but it is still necessary to analyze the correlation between pre-evacuation time and queuing time. Figure 4.9 shows that for short pre-evacuation periods, a larger time is taken for queuing compared to shorter queuing time in longer pre-evacuation period. An inverse correlation is observed between pre-evacuation time and queuing time. Based on this, the evacuation planner should anticipate a higher crowd level at some exits in planning successful emergency evacuation procedure. When a large number of occupants decide to leave the building in short time, a long queuing line will be formed thus may cause blockage at some exits, especially at the ground floor exit door.

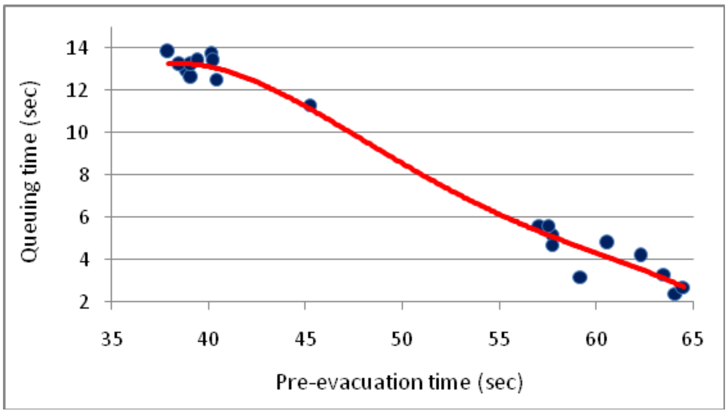


Figure 4.9: Pre-evacuation time versus queuing time

It has been established that the main cause of delay in pre-evacuation is ignoring the emergency alarm notification. On average, 41% of pre-evacuation phase depend the occupant's decision of either to leave immediately or to ignore immediate leaving. It is interesting to study in detail, why people take a big portion of time for this action? The lack of trust in the emergency system is one of the reasons that makes occupants tend to ignore the emergency notification or alarm signal. Based on our survey, 25% of alerted emergency alarms were the nuisance (false) alarms. The frequent occurrences of nuisance alarms may cause some occupants to loose confidence of the emergency alarm system in the building and hence will not heed to future emergency alarm notification. Therefore, the in high-rise buildings should follow the standard specifications and must be accurate and reliable.

A large portion of time is also spread on saving valuable items before leaving the building. This action, preparing the valuable items, takes 35% of pre-evacuation phase. This is a common action among most of the occupants even though the standard procedure do not allow for any other activities besides leaving the building immediately. But most of the survey respondents placed this action as their top priority action (53% of weightage) before leaving the building. Valuable items and important documents are the most classified items to be saved by the occupants.

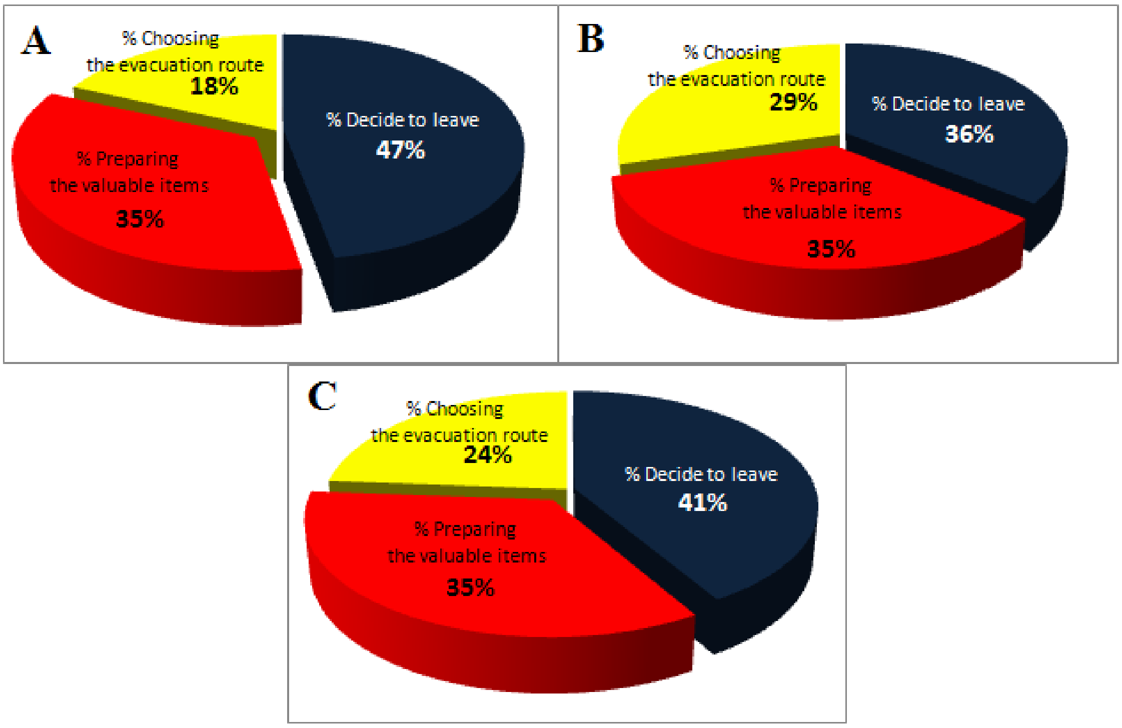


Figure 4.10: Time consumption for each pre-evacuation activity according to (A) Exponential distribution; (B) Weibull distribution; (C) average of Exponential and Weibull distributions.

Choosing the evacuation route takes 24% of total pre-evacuation time. Some occupants still need to confirm the best choice and get shortest route out of the building. Different knowledge of building layout or the familiarity of building environment of each occupant and lack of confidence in the exit signs may be the root causes to this problem. Occupants who are familiar with the building environment would be able to get the shortest route and provide effective guidance for the other occupants to evacuate the building safely.

A detailed proportion of each activity in the pre-evacuation phase as part of TET is depicted in figure 4.11. In the case of hostel evacuation, recognition activity in pre-evacuation phase contributed 24.8% of TET. The evacuation planner should focus on this activity because the beginning of this phase is the onset of TET. Some proposed improvements to minimize the recognition phase are presented in the next subchapter. The start of egress during pre-evacuation also presents a significant contribution to TET, according to 21.1% of TET. While the action of investigating or choosing path forms 14.5% of TET.

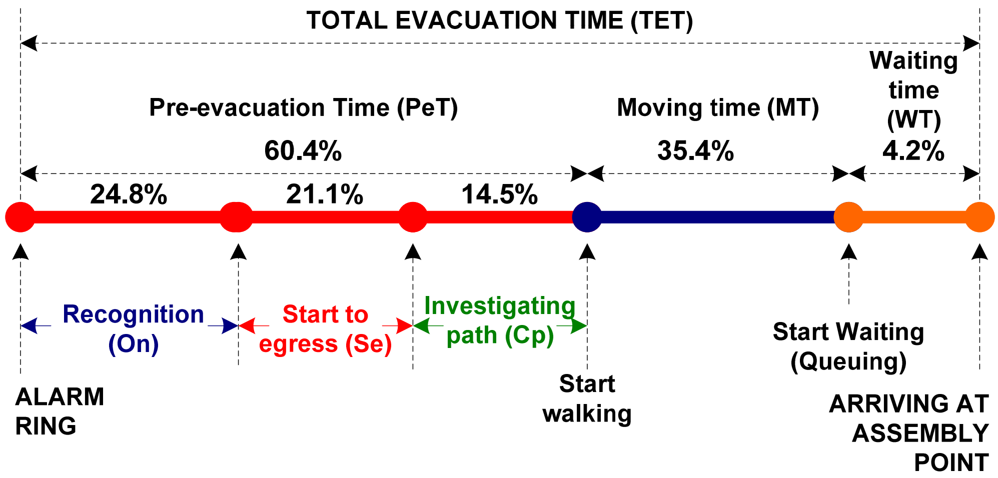


Figure 4.11: Time proportion for each phase in hostel evacuation

An evacuation performance chart has been provided as one of the output of SEEP 1.5. By using this chart, a user is able to evaluate the simulation process by plotting the % of saved evacuee against time. The evacuation performance charts are shown as in figure 4.12 and figure 4.13. In the case of hostel simulation, two different types of distribution as SVN input, i.e.: Exponential and Weibull, has been used to obtain different outputs. The simulation for 180 occupants, using the Exponential distribution takes longer TET than the Weibull distribution.

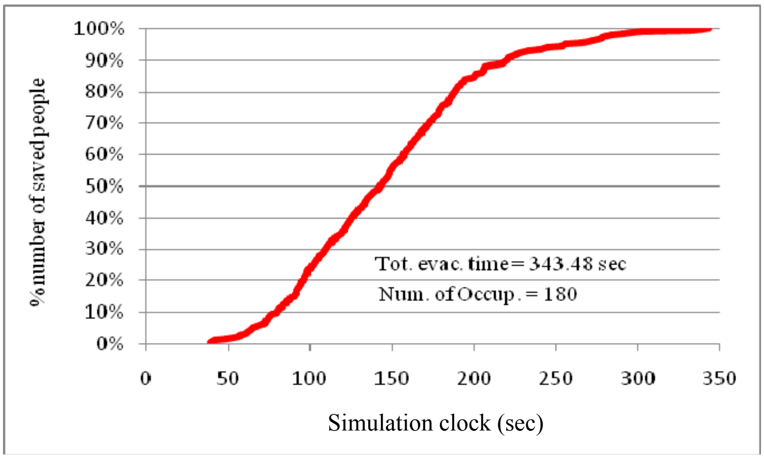


Figure 4.12: Simulation clock versus number of saved people, from Exponential distribution on SVN

From both evacuation performance charts, a time delay between the alarm ring and the first occupant to leave the building is observed. Respectively, the simulation results with Exponential distribution on and with Weibull distribution show that approximately 40 seconds and 30 seconds were wasted. The detail of time wasting generation before leaving by each occupant can be found in SEEP 1.5 report (Appendix A3).

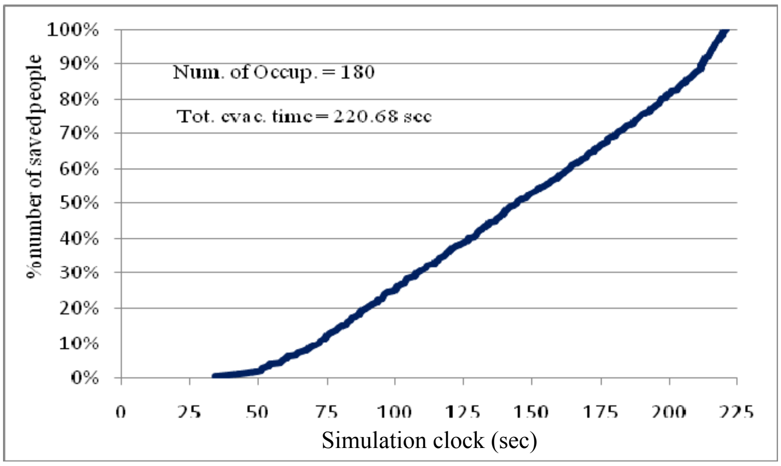


Figure 4.13: Simulation clock versus number of saved people from Weibull distribution on SVN.

4.5. Pre-evacuation time reduction analysis

One of the objectives of this thesis is to propose an improvement to reduce the TET by minimizing the wasting processes. In previous subchapters, detail time consumption of each activity in the evacuation phase has been provided using SEEP 1.5. Now, the focus shall be on pre-movement phase, which takes about a half of TET. Some discussions related to pre-movement time parameters are provided in order to propose for some improvement activities.

Based on our evacuation survey and previous observation report, building occupants are usually slow in responding to fire alarm notification or emergency signals. Most of the time, they tend to completely ignore the signal and continue with their activities. As stated by (Proulx, 2000), there are three possible reason why people ignore the alarm signal, i.e.: failure to recognize the alarm signal as an emergency alarm, distrust of the emergency system because of frequent nuisance alarms, and/or unable to hear the emergency warning through the alarm. For detail description of recognition phase, figure 4.14 represents these three possible reasons to ignore the alarm signals.

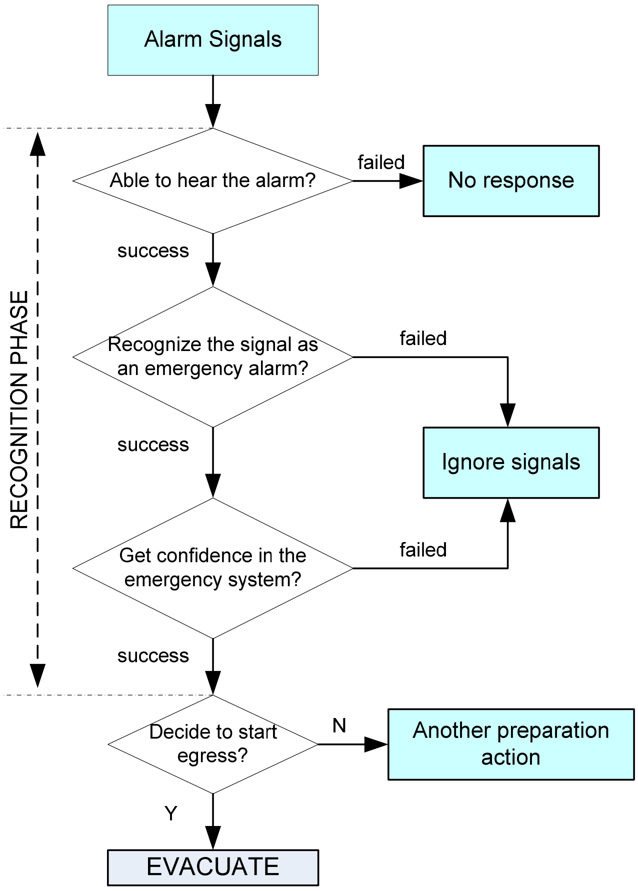


Figure 4.14: Emergency alarm recognition phase in evacuation planning

The audibility of alarm signal becomes the root problem of failure to hear the alarm. A study conducted by (Proulx, 1995) showed that around 25% of total two building occupants did not hear the alarm signal. This shows that the number of alarms installed in the building is insufficient. Therefore, building managements must consider optimal number of emergency alarms at appropriate locations in the buildings. It is also important to test audibility of the emergency alarms in every available room in a high-rise building.

In cases when the emergency signals were audible to hear by the occupant, there is another possibility that the occupants failed to recognize the signals as the emergency alarm signals. They might identify the emergency signal as another type of signal, such as security door alarm, criminal alarm, or elevator fault warning (Proulx, 2000). Therefore, the emergency alarm should follow the standard evacuation signal provided by ISO 8201: Audible emergency evacuation signal. The Temporal-Three pattern alarm has been introduced as the standard alarm signal for emergency evacuation.

There are some examples of nuisance alarm, such as false alarm, alarm in the event of evacuation drill, and test alarm. Since many nuisance alarms sounded in the building, the occupants might assume the alarm signal as a false alarm. Our survey results show that 30% of sounded alarms is due to evacuation drill and 25% is false alarm. Naturally, this condition makes the trust level against emergency system become lower and less confidence. High precision of emergency detection device should be maintained by building management to avoid the nuisance alarm.

(Proulx, 2000) states eight ways to increase the occupant response of emergency alarm.

a. Apply ISO 8201 standard signal pattern i.e.: the Temporal-Three alarm
b. Maintain standard safety plan in high-rise buildings and circulate the appropriate procedures to the occupant.
c. Perform the evacuation drill at least twice a year.
d. Increase the alarm reliability to minimize the number of nuisance (false) alarms
e. When the alarm rings, the environment ambience should be changed as fast as possible.
f. Live messages are more effective and moreover supported by direct broadcast information sharing though television.
g. Conduct special training for floor wardens to prompt occupant movement
h. Clarifications of real conditions are needed as feedbacks to occupants for any alarm activation on the high-rise buildings.

A sensitivity analysis on pre-movement phase was carried out in order to investigate some possibilities of reducing TET. The pre-evacuation time in SEEP 1.5 that was generated by the SVN model involved three parameters, i.e.: *leaving* *probability*, *preparing probability*, and *choosing probability*. The generation of recognition time (decide to leave, p_{on}) depends on leaving probability, start to egress time (preparation, p_{se}) generation depends on preparing probability, and time to investigate the path (choosing the route, p_{cp}) depends on choosing probability. In the sensitivity analysis, only two parameters were modified; these are *leaving probability (p_{on})* and *choosing probability (p_{cp})*. The preparation or rescuing activity was not considered for modification since this activity was always performed by most occupants during pre-evacuation phase.

The sensitivities of leaving probability and choosing probability were studied to measure their effects on the TET and preparing probability was set at a constant value. As depicted in figure 4.15, the effect of increasing the leaving probability is a reduction in the TET. In reference to the hostel evacuation, if the building management had been able to notify all occupants to evacuate immediately once the alarm has rung (leaving probability = 1 or recognition time ≈ 0) there was an opportunity to reduce the TET to ± 41.2% (compared with normal conditions where leaving probability = 0.28). As seen in figure 4.15, TET can be reduced by decreasing the leaving probability. This pattern is applicable to any different choosing probability.

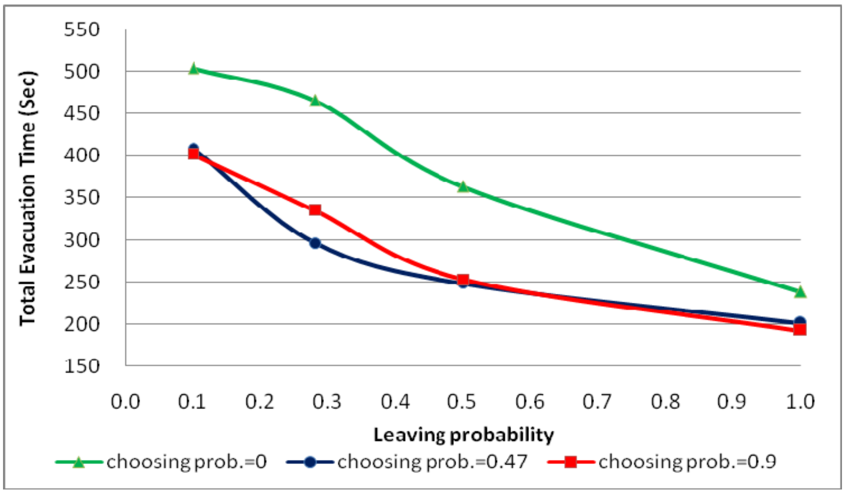


Figure 4.15: Pre-evacuation parameters versus TET

However, an evacuation planner has to anticipate a high crowd level which has a positive correlation with the increasing value of leaving probability. Figure 4.16 shows the patterns of three different leaving probabilities versus crowd level. Increasing leaving probability means increasing the pre-evacuation response that makes many occupants decide to evacuate all at once. By improving the leaving probability, the crowded level may increase up to 21% (with leaving probability = 1).

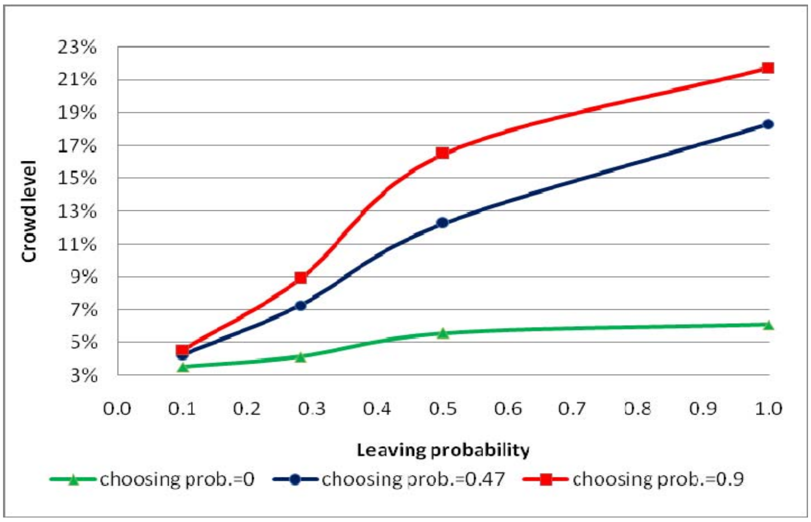


Figure 4.16: Pre-evacuation parameters versus crowded level

The size of crowd also is an indication of ground floor utilization during evacuation. It is, therefore, necessary to analyze ground floor utilization since the highest possible traffic would appear at the ground floor. In normal conditions, ground floor utilization is approximately 37%. But in emergency situation when all the occupants are able to eliminate the recognition phase or leaving probability = 1, ground floor utilization can reach up to 67%. The pattern of ground floor utilization is depicted in figure 4.17.

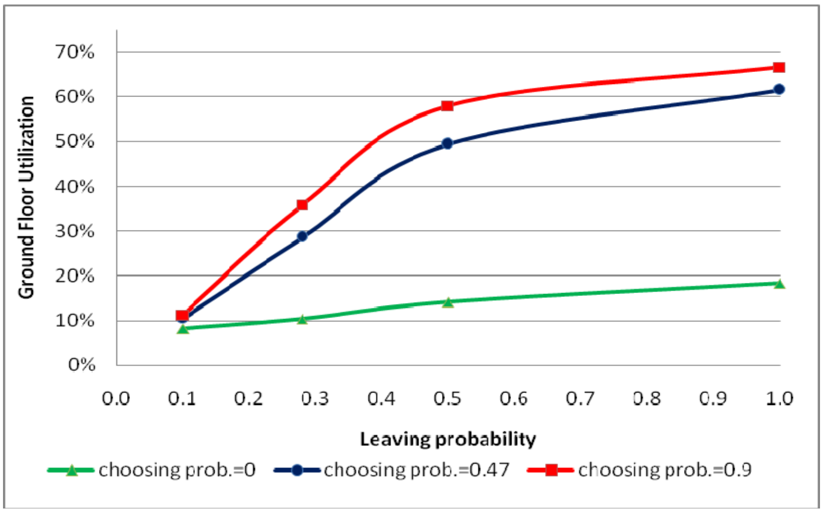


Figure 4.17: Pre-evacuation parameters versus ground floor utilization

Furthermore, the sensitivity analysis of pre-movement parameters is continued to observe correlation between pre-movement parameter's changes and evacuation time. Overall, the TET decrease when the pre-movement parameters increase. The shortest TET (192.6 seconds) is achieved when all the occupants able to eliminate the recognition phase or leaving probability = 1 and choosing probability = 0.9. Longer TET (503.7 seconds) is performed where leaving probability = 0 and choosing probability = 0.9. Figure 4.18 shows the correlation between leaving probability and other pre-movement parameters. Preparing and choosing probability decline followed the growth of leaving probability. Higher leaving probability means the occupant perform higher confidence level to pursue the evacuation order. The higher confidence in the evacuation system will enhance the occupants respect to the existing emergency planning.

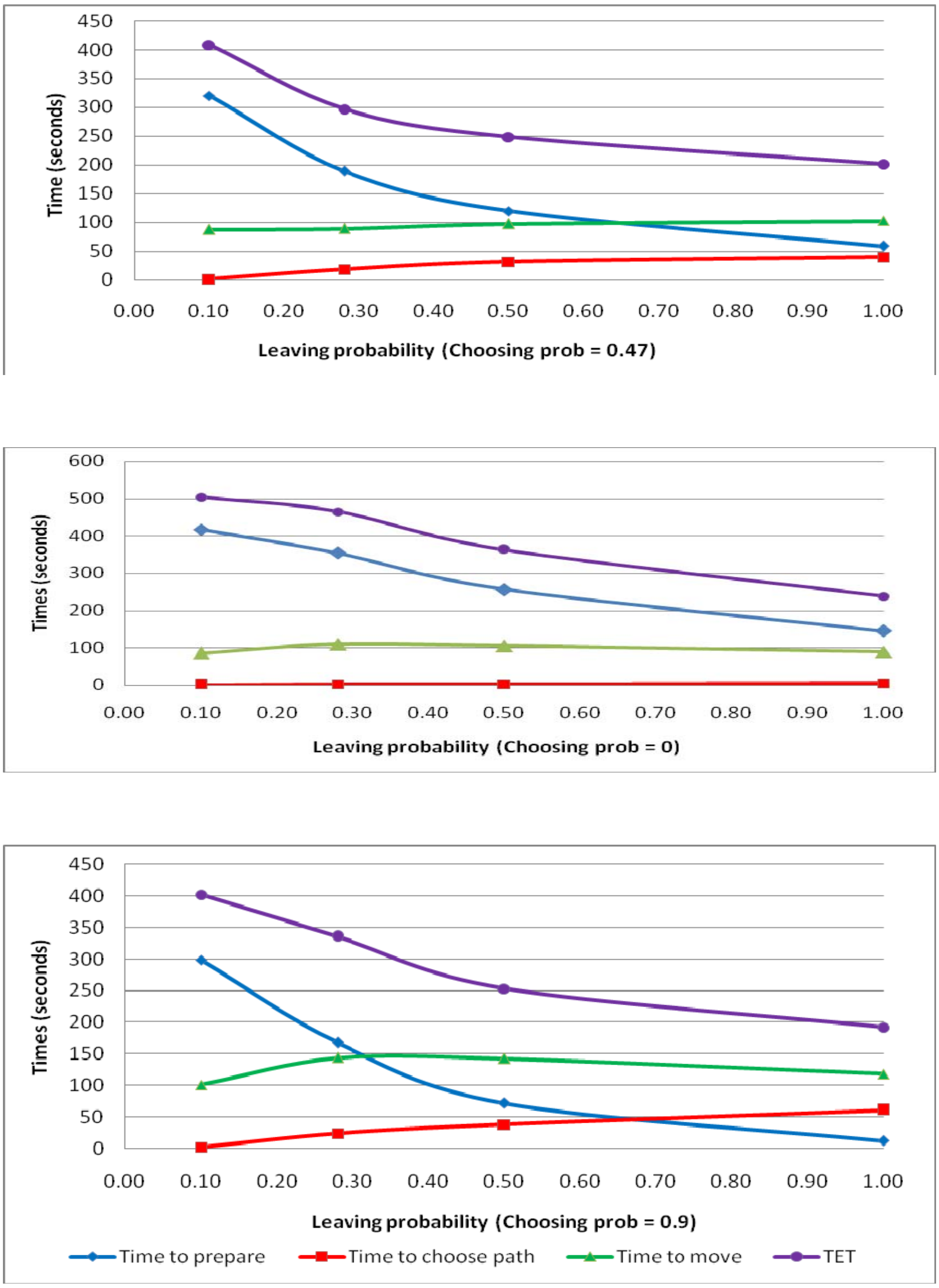


Figure 4.18: Correlation between pre-evacuation parameter and evacuation time

4.6. Summary

Pre-evacuation phase is critical phase in high-rise buildings evacuation. On the beginning part of this chapter, evacuation drill data from previous study shows that more than 50% of TET has formed during pre-evacuation phase. This chapter also provided our evacuation survey result which one of the results shows that only 39% of respondent leave the building immediately as their first action when heard the alarm signal. The rest respondent take the other actions mean ignoring the alarm signal. The evacuation results also present the probability value of some appropriate activities in pre-evacuation.

In this chapter, human cognitive behavior model has been built in the evacuation simulation. Some impact of wasting actions during pre-evacuation phase can be studied with SEEP 1.5. In the case of hostel evacuation, simulation result has provided a time proportion for each phase in evacuation. Pre-evacuation time has taken 60.4% of TET, movement time has taken only 35.4% of TET, and queuing time has taken 4.2% of TET. Recognition of alarm signal during pre-evacuation phase has contributed 24.8% of TET, 21.1% of TET is needed by start to egress activities, and 14.5% is needed by investigating path actions.

In chapter 5, the other investigation for time consumption in movement phase is provided. Next chapter will present the comparison between familiarity of environment wayfinding method and the proposed ACO wayfinding method.

CHAPTER FIVE: FEASIBLE ROUTE DETERMINATION USING ANT COLONY OPTIMIZATION

Several wayfinding methods that are usually employed in an evacuation process are discussed in this chapter. Various wayfinding methods were compared in order to study the importance of dynamic guidance. A wayfinding method with modified exit signs as smart agents to guide the occupants dynamically during evacuation phase is proposed. The smart agent, embedded with ACO, has the capability to determine the most feasible evacuation route. Finally, comparison was made between the most common wayfinding method, familiarity of environment and the ACO wayfinding method in order to test our hypothesis.

5.1. Introduction to Ant System

Ants are social insect that live together in a colony system. One of the well-known behaviors of ants is their effective cooperation in finding the food or sources of food. Ants, the blind insects, are able to track the shortest path between their nest to the food sources and back. It is found that every ant has pheromone, the medium that is used to communicate information among ants along their journey. Each ant marks the path by leaving a trail of pheromone in varying quantities on the ground. The next ant would able to track the marked path and will decide to follow with a certain probabilistic value, and also strengthen the chosen path by putting new pheromone itself. This kind of communication is called *stigmergy* process (Dorigo, et al., 2004).

(Dorigo, et al., 1997) who introduced the ACO, described an example of ant tracking process as shown in figure 5.1. After an ant has found the source then other ants will follow by walking from the nest on A, to the source on E, and vice versa. When an obstacle cuts off the path between A and E, the ants at position B (walking from A to E) and also the ants at position D (walking from E to A) must to choose whether to turn right (through point H) or turn left (through point C). They have the same probability value to choose either point H or point C. The path BCD is shorter than the path BHD. Therefore, the first ant that choose the path BCD will reach point D before the first ant that chooses the path BHD. Once the ants walking from E to D find the first ant from path BCD, they will follow the same path. Each ant that passes through BCD will leave a trail of pheromone. Consequently, the amount of pheromone in path BCD will be higher than path BHD. The number of ant following path BCD will increase, on the contrary, the number of ant following path BHD will decrease. Eventually, path BHD will be not chosen anymore.

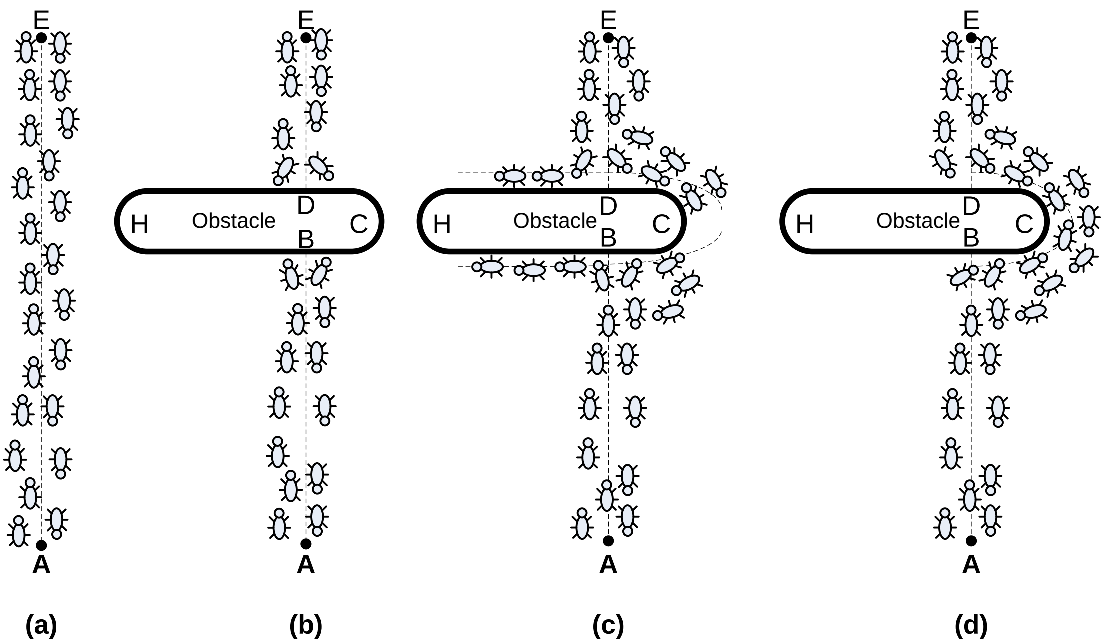


Figure 5.1: Stigmergy process of real ant. (a) Ants walking from point A to point E. (b) An obstacle appears, ants must choose whether to turn right or left. (c) Ants following the shortest path between point A and point E. (d) Route ABCDE has been formed. (Dorigo, et al., 1996).

In the simulator, the ants start the tour to find the shortest route by choosing a defined node or town randomly and one node will place by one ant. Every node will be visited by the ant to get a complete tour in one circle tour. The node selection by an ant is decided upon using a probabilistic function called state transition rule, by considering the visibility (inversion of distance) and the amount of pheromone on the trail. (Dorigo, et al., 1997), define that transition probability from node i to node j for k^{th} ant as:

$$p_{ij}^{t}(t) = \begin{cases} \dfrac{[\tau_{ij}(t)]^{\alpha}.[\eta_{ij}]^{\beta}}{\sum_{k \in allowed\ k}[\tau_{ik}(t)]^{\alpha}.[\eta_{ik}]^{\beta}} & if\ j \in allowed\ k \\ 0 \quad otherwise \end{cases} \tag{5.1.}$$

Where $\tau_{ij}(t)$ as the intensity of trail on edge (i , j) at time t and η_{ij} as the visibility of an ant ($\eta_{ij} = 1/d_{ij}$).

One of the major differences between a real ant and an artificial ant is artificial ant will have some memory, using tabu list. A tabu list contains a list of visited nodes and this list will avoid tour repeatability, i.e., one ant not be allowed to visit a node more a once. When the tabu list is full, a global pheromone updating rule will be applied to avoid stagnation process. The distance of every path achieved by an ant will be calculated and new pheromone will be placed on every node based on the selected path. The shorter route achieved by an ant will be marked by placing more pheromone on that node, and the shortest route will be memorized in the tabu list.

The trail intensity is updated according to the following formula (Dorigo, et al., 1997):

$$\tau_{ij}(t+n) = p.\tau_{ij}(t) + \Delta\tau_{ij} \tag{5.2}$$

where p is a coefficient representing the evaporation of trail between time t and t + n (p value must be <1 to avoid unlimited accumulation of trail). The quantity of substance per unit of length of trail (i,j) is:

$$\Delta\tau_{ij} = \sum_{k=1}^{m} \Delta\tau_{ij}^{k} \tag{5.3}$$

(Dorigo, et al., 1997) define the ant-cycle algorithm as below:

1. Initialize: set time counter (t) = 0, set circle counter (NC) = 0, trail intensity ($\Delta\tau$)=0 ant place the m ants on the n nodes
2. Set tabu list index (s) = 1 an place the starting town of k^{th} ant in $tabu_k(s)$.
3. Set s=s+1 and repeat until tabu list is full, every ant choose the town j to move, with probability $p_{ij}^{k}(t)$ and insert town j in $tabu_k(s)$.
4. Move the k^{th} ant from $tabu_k(n)$ to $tabu_k(1)$ and compute the length L_k. Update the shortest route found. Set $\Delta\tau_{ij}^{k} = \begin{cases} \frac{Q}{Lk} & if\,(i,j) \in \text{ tour described by } tabu_k \\ 0 & otherwise \end{cases}$ and

   $\Delta\tau_{ij} = \Delta\tau_{ij} + \Delta\tau_{ij}^{k}$
5. Compute $\tau_{ij}(t+n) = p.\tau_{ij}(t) + \Delta\tau_{ij}$
6. Set $t = t + n$, $NC = NC + 1$ and $\Delta\tau_{ij} = 0$

5.2. Proposed expansion to the Ant System

The original transition probability function of Ant System considers the intensity and the distance. This probability function can solve the shortest route problem. However, in this thesis, the minimum distance is not the only goal under consideration. But also consider any physical factors or any source of dangers as the route's obstacle. Since the original probability function of Ant System does not have any consideration of an obstacle factors, the expansion to the original Ant System are required.

A new factor is added by considering the physical obstacle that can be found in buildings such as fire location, damaged facilities, bottleneck problem and obstacle at the exit corridor. A route, where a physical obstacle has occurred, should not be chosen.

The transitional probability rule as given in (5.1) will determine the next route to be chosen by an ant during route detection. An expansion to the transitional probability rule is proposed by adding a new variable, i.e.: traffic on the node i to j (ω_{ij}), as given in (5.4).

$$p_{ij}^{k}(t) = \frac{[\tau_{ij}]^{\alpha}.[\eta_{ij}]^{\beta}.[\omega]^{\lambda}}{\sum_{k\ \varepsilon\ allowed\ k}[\tau_{ij}]^{\alpha}.[\eta_{ij}]^{\beta}.[\omega]^{\lambda}} \quad (5.4)$$

where α, β, λ are parameters that control the relative importance of these 3 variables of transitional probability rule.

The traffic variable (ω_{ij}) parameter is defined as the inversion of physical obstacle ($1/pob_{ij}$), where pob_{ij} is weight of the physical obstacle from node i to node j. The value of pob_{ij} must be set as a ratio number e.g.: the utilization of corridor or staircase. The traffic variable will not be updated during the ant algorithm process; instead, it will be updated during the simulation.

5.3. Comparison of Two Wayfinding Methods

Route determination is critical in high-rise buildings evacuation. In normal situation, the occupants will not face any problem to exit from the building. But when a real emergency situation arose, there will be much panic and crowded situations in the building. Under this circumstance, an accurate decision is required not only to determine the shortest but also the safest evacuation route.

Previously, some methods of finding the escape route from high-rise buildings during emergency evacuation have been clearly discussed in chapter 2. In normal evacuation processes, most of the occupants would depend on their knowledge of the building environment and facilities. Most commonly, their decisions would be based either on instinct or supported by previous experiences. Familiarity of environment becomes important in building a complete cognitive map of the building complex. A complete cognitive map will enable a more precise determination of the evacuation route.

Unfortunately, the route determined based on the familiarity of environment is not able to identify the positions obstacles in the building. When a real obstacle appears at certain building location, there will be a possibility of some occupants being trapped at the obstacle area. Even a group leader who has a very good knowledge of the building environment still needs to get the overall building status in order to avoid the real physical obstacle. Most of the previous studies in evacuation did not consider the physical obstacle that blocked the evacuation flows when they were simulating the leader as the guidance during evacuation.

Learn from (Murakami, et al., 2002) and (Pelechano, et al., 2006) who have simulated the behavior of a leader and its contributions in evacuation process, have shown that a shorter evacuation time can be obtained by a guidance from a leader than the evacuation without any leader. A leader can be defined as a trained occupant, safety officer, fire fighter, or a police officer.

Since in reality, it is difficult to find a leader among the occupants during an emergency situation and the leader's knowledge of the building environment is not known, therefore this thesis proposes the modified exit sign as the dynamic guidance from the evacuation process. Exit sign is one of the emergency facilities in the building to indicate the evacuation routes to the assembly point. In our simulation, the exit sign has been modified as a smart agent where an ACO has been embedded on the emergency exit agent. ACO is the optimizing method to calculate the shortest route based on some percept of the real emergency situation inside a building. The emergency exit agent will receive some updated percepts from the supply agents (staircase agent and agent corridors/halls), such as physical obstacle status, queuing status and occupant location in the building. All occupant agents will follow the evacuation route that has been determined by emergency exit agent.

In chapter 3, agent-based conceptual model has been provided using Prometheus methodology. Emergency exit agent has a capability to determine the feasible route. The route determination from Emergency exit agent will be shared to the Occupant agent as the guidance during the evacuation process. To summarize all the process of ACO wayfinding and interaction between occupant and emergency exit agent, the detail step high level ACO wayfinding diagram has depicted in Figure 5.2.

Occupant agent performs their response to the emergency notification by following the cognitive behavior model during the pre-evacuation phase. At the same time, the Emergency exit sign will also calculate the possibly route using ACO algorithm and considering the risk level of each route. Once the occupant agent take a decision to leave the building, they will informed by the Emergency exit agent about the feasible route should be followed during the evacuation.

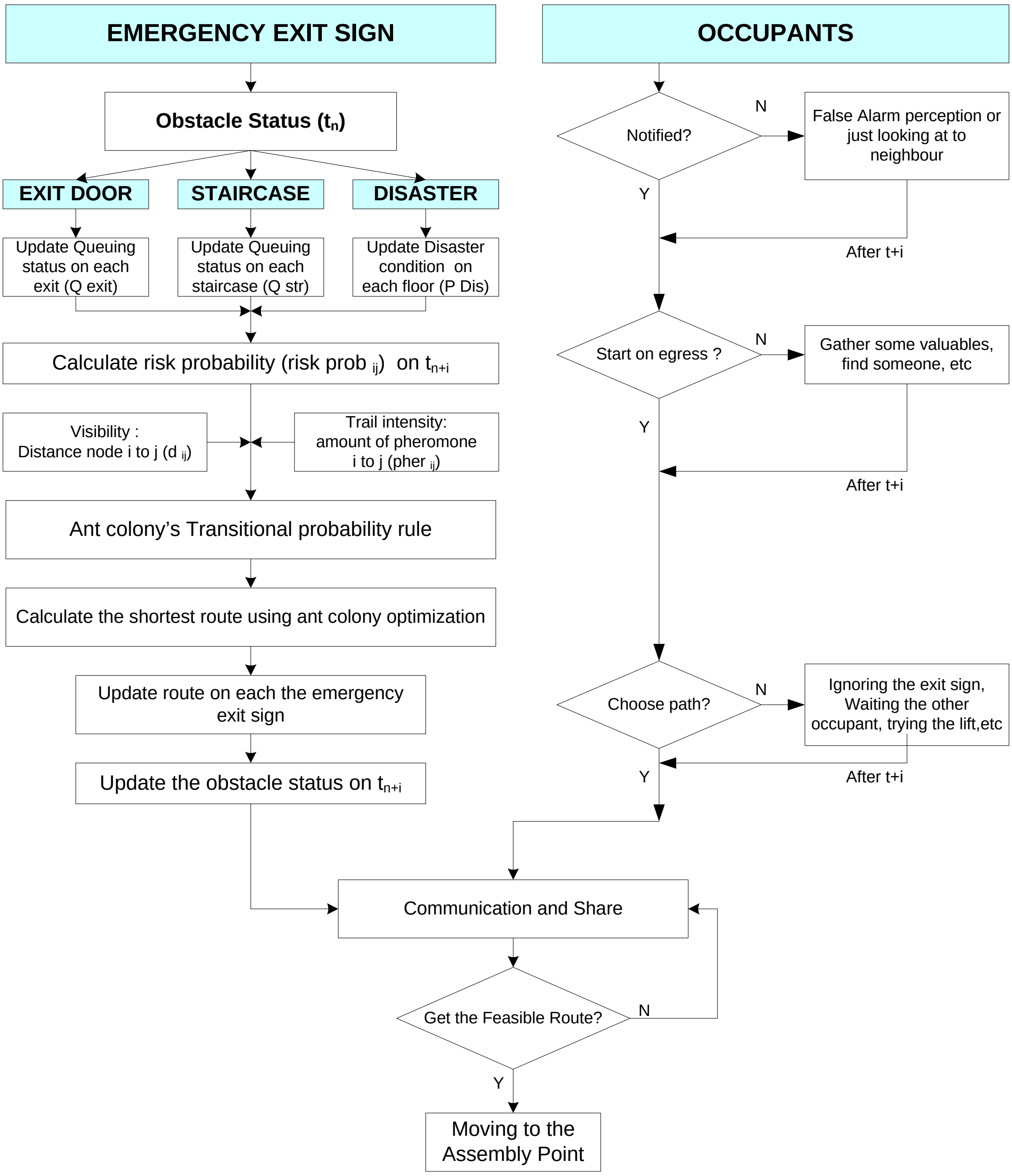


Figure 5.2: A high level ACO wayfinding diagram

5.4. Simulation Results

SEEP 1.5 has been designed and prepared to simulate some defined scenarios. From the input menu, by selecting the two wayfinding method option, i.e., the exit method based on familiarity of environment or ACO determination, the first scenario is ready to observe. The input menu of SEEP 1.5 is presented in appendix A. A hostel building with 180 occupants is taken as the case problem. A random pre-evacuation time generation is applied to run these scenarios and the movement phase will be considered as the performance indicator compare to the two methods. The movement time includes the time to move and time to queue only.

5.4.1. Scenario 1 (without obstacle)

The first wayfinding method, familiarity of environment, is the most common route based on the occupants' routine and usually is the nearest staircase and/or exit from their existing position. In the case of hostel evacuation, an occupant from room R3.1.1 (level 4) takes the network route 1 – 3 – 4 – 12 – 20 – 28 – 32 – 33, as seen in figure 5.3. The clear evacuation route from the hostel building is as depicted in figure 5.4. Usually, the route based on the familiarity of environment in normal situation is straight forward. This route should be the shortest route as formed by their daily experience.

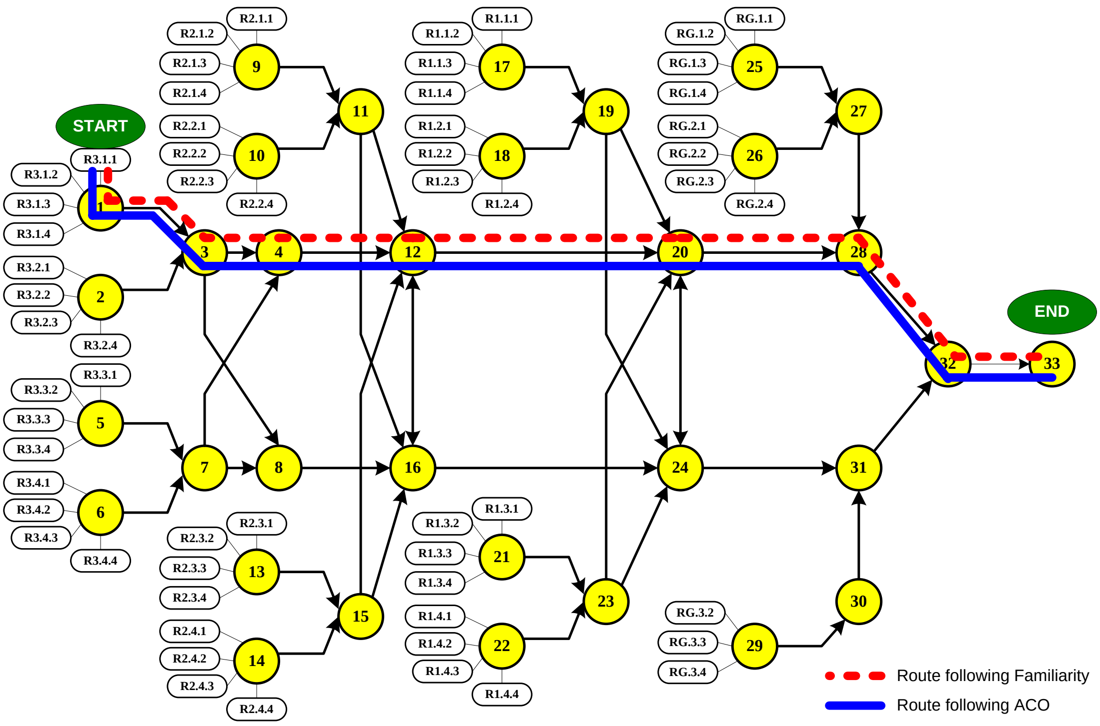


Figure 5.3: Evacuation route determination without obstacle: Familiarity of environment based method versus ACO determination method

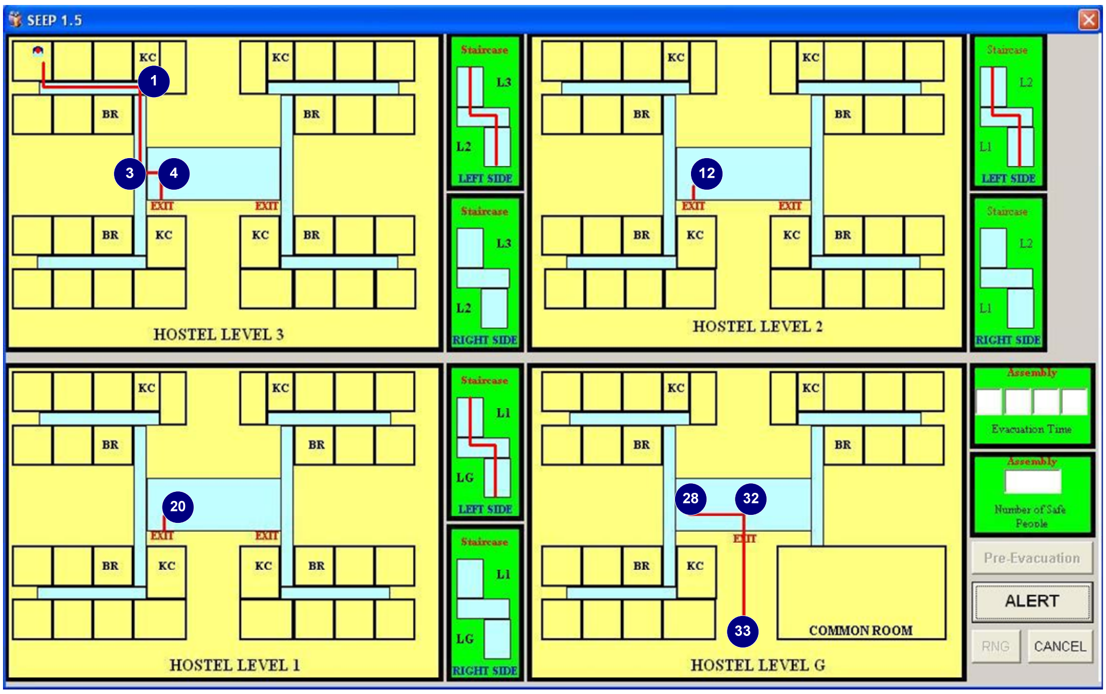


Figure 5.4: Evacuation route description and node representations on building layout

Next, the ACO wayfinding method with emergency exit agent as the dynamic guidance was applied to the simulation to determine the evacuation route. As explained before, the ACO wayfinding method considers the distance and also the physical obstacles. Table 5.1 shows that the route that has been determined by ACO for the occupants of room R.3.1.1 to escape through the same route as the familiarity based method is 1 – 3 – 4 – 12 – 20 – 28 – 32 – 33 (refer to the network model's node notation for hostel evacuation). Most occupants guided by ACO take the same route as familiarity wayfinding and the detail routes for each occupant can be seen on appendix A.

Table 5.1: Examples of route determination on hostel level 3 and level 2 without obstacle

		WITHOUT OBSTACLE	
OCCUPANT NO.	**LOCATION**	**ROUTE FOLLOWING FAMILIARITY**	**ROUTE FOLLOWING ACO**
1	Level 3 Block 1	1-3-4-12-20-28-32-33	1-3-4-12-20-28-32-33
13	Level 3 Block 3	5-7-8-16-24-31-32-33	5-7-8-16-24-31-32-33
25	Level 3 Block 2	2-3-4-12-20-28-32-33	2-3-4-12-20-28-32-33
37	Level 3 Block 4	6-7-8-16-24-31-32-33	6-7-8-16-24-31-32-33
49	Level 2 Block 1	9-11-12-20-28-32-33	9-11-12-20-28-32-33
61	Level 2 Block 3	13-15-16-24-31-32-33	13-15-16-24-31-32-33
73	Level 2 Block 2	10-11-12-20-28-32-33	10-11-16-24-31-32-33
85	Level 2 Block 4	14-15-16-24-31-32-33	14-15-12-20-28-32-33

The performance of these two wayfinding methods is compared in term of total movement time, including movement time and queuing time. The total movement time of the two methods can be set as equal by defining, H_0: $\mu_{ACO} = \mu_{FAM}$.

A statistical analysis, t-test, was conducted to evaluate the above hypothesis and the t-test result is presented on table 5.2. Based on t-test result, it can be interpreted that there is no significant different in movement time perform by both wayfinding methods ($t_{stat} < t_{critical}$).

Table 5.2: t-test for total movement time taken by Familiarity of Environment based method Versus ACO based method without obstacle (scenario 1)

	ACO	*FAMILIARITY*
Mean	349.22	350.98
Variance	320.43	89.48
Observations	10.00	10.00
Hypothesized Mean Difference	0	
df	9.00	
t Stat	-0.26	
P(T<=t) one-tail	0.40	
t Critical one-tail	1.83	

This shows that in the absence of obstacles, the simulation results give the same route either with ACO or familiarity of environment methods. Familiarity of environment is formed by routine processes, recognizing past experiences, retrieving successful experiences and carrying out the routines (Pan, et al., 2006).

5.4.2. Scenario 2 (with obstacle)

Scenario 2 was simulated with the presence of an obstacle in order to show the difference in performance between a local based decision and the decision based on overall situation in a building. An obstacle was placed at the end of the left staircase - level 2 or between node 12 and node 20 (refers to network model). Figure 5.5 shows the location of the obstacle in the building.

As described in figure 5.6, the obstacle has impeded the path through the left staircase L2 - L1 (level 2 to level 1). That obstacle has forced all occupants who have chosen that route to turn back through another staircase on the right side. The occupants coming from node 1 (level 3 block 1), node 2 (level 3 block 3), node 9 (level 2 block 1), and node 10 (level 2 block 3) have to choose the right staircase L2-L1 to avoid the obstacle beyond node 16.

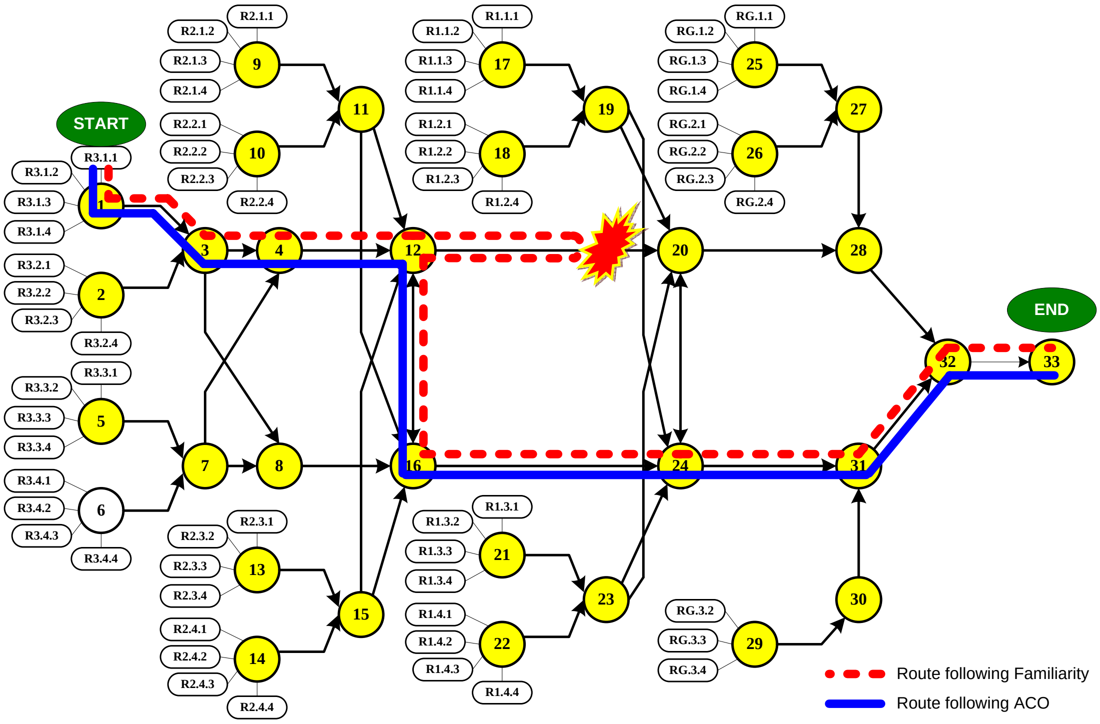


Figure 5.5: Evacuation route determination with the presence of an obstacle: Familiarity of environment based method versus ACO determination method

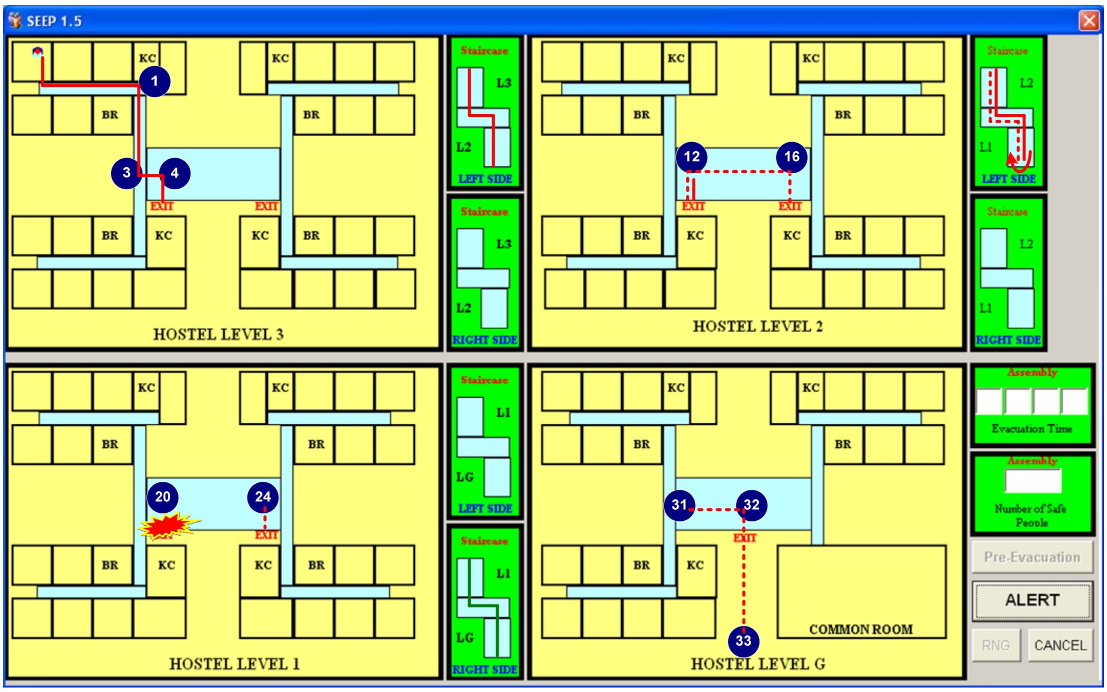


Figure 5.6: Evacuation route description for the backtracking movement on staircase L2-L1 (left side)

In scenario 2, both familiarity of environment method and ACO wayfinding method were applied in the simulation. In the simulation using familiarity wayfinding method, some occupants who were trapped at the left staircase L2-L1 had to turn back to the right side. This movement caused a bidirectional crowd flow on that right staircase. In comparison to ACO wayfinding method, most of the occupants who followed the route determined by ACO were able to avoid the obstacle by selecting the route through the right staircase L2-L1 directly. The route determined by ACO has considered the obstacle thus the blockage route was avoided by choosing the right side staircase L2-L1 or from node 12 across to node 16. Some examples of route determination from both wayfinding are presented in table 5.3.

When a physical obstacle appeared between node 12 and node 20, pob_{i20} was defined as equal to 1; ACO exit method determined the feasible route by avoiding node 20. Even though most of occupants choose the feasible route through the right staircase L2-L1, there is still a possibility that an occupant could be trapped on node 20 (an occupant agent can possibly ignore the information by emergency exit agent).

Table 5.3: Examples of route determination on hostel level 3 and level 2 with an obstacle

		WITH OBSTACLE	
OCCUPANT NO.	LOCATION	ROUTE FOLLOWING FAMILIARITY	ROUTE FOLLOWING ACO
1	Level 3 Block 1	1-3-4-**12-20-12**-16-24-31-32-33	1-3-8-16-24-31-32-33
13	Level 3 Block 3	5-7-8-16-24-31-32-33	5-7-8-16-24-31-32-33
25	Level 3 Block 2	2-3-4-**12-20-12**-16-24-31-32-33	2-3-4-12-16-24-31-32-33
37	Level 3 Block 4	6-7-8-16-24-31-32-33	6-7-8-16-24-31-32-33
49	Level 2 Block 1	9-11-**12-20-12**-16-24-31-32-33	9-11-16-24-20-28-32-33
61	Level 2 Block 3	13-15-16-24-31-32-33	13-15-16-24-31-32-33
73	Level 2 Block 2	10-11-**12-20-12**-16-24-31-32-33	10-11-16-24-31-32-33
85	Level 2 Block 4	14-15-16-24-31-32-33	14-15-16-24-20-28-32-33

Table 5.4 shows the analysis of these two methods using t-test. Based on the statistical test, it can be interpreted that the total movement time taken by familiarity of environment wayfinding method is different significantly from the total movement

time guided by ACO wayfinding method (t_{stat} > $t_{critical}$). In the case of hostel evacuation, the average clearance time taken by familiarity wayfinding method is **21.6%** longer than the average clearance time taken by ACO wayfinding method. Further discussion related to this finding is discussed in the next sub chapter.

Table 5.4: T-test for total movement time taken by familiarity of environment based method versus ACO based method with obstacle (scenario 2)

	ACO (Obs)	*FAMILIARITY (Obs)*
Mean	347.66	367.04
Variance	316.62	248.98
Observations	10.00	10.00
Hypothesized Mean Difference	0	
df	9.00	
t Stat	-2.09	
P(T<=t) one-tail	0.03	
t Critical one-tail	1.83	

5.5. Shortest Route, not always a Feasible Decision in Evacuation Process

The main objectives in evacuation planning of a high-rise building is to bring people out of the building safely. This objective clearly states that successful evacuation process means saving all building occupants without any injuries. TET and number of saved people can be used as the primary indicator in managing the evacuation plan. Short clearance time becomes the critical parameter in order to perform a successful evacuation process. However, many factors must be considered in getting the shortest clearance time from the physical building itself including the unpredictable behavior of human.

The simulated results of the two wayfinding methods have shown that the ACO wayfinding method has a shorter clearance time compared to the familiarity of environment wayfinding method. When physical obstacle(s) appeared in the building, untrained occupants with less experience and unable to locate the obstacle position might be trapped at the impeded location. Based on that possible conditions and also from the simulation (scenario 2), an evacuation planning must be prepared to handle the worst conditions inside a building, especially the preparedness for highly dynamic evacuation.

Achieving short TET is associated with successful evacuation process. It is true that faster TET means that a larger number of people could be saved in an evacuation. In normal situation, the path believed as the shortest exit out of the building is formed by the daily routine of movement. However, based on the experiment for scenario 2, when obstacles must be considered, the shortest route does not necessarily mean the safest route anymore. The appearance of a physical obstacle would obstruct the route and/or pose danger.

In an emergency situation, the occupant would choose the most familiar route to them and tend to ignore other alternatives. Usually, building occupant make a decision to use familiar exits, such as where they entered the building. Their familiarity of the environment is formed by their past experiences and was built into a cognitive map of the building. In the event of a real emergency situation, most people would panic and might loss their rationale decision. Under such circumstances, their current cognitive map became the simplest knowledge to extract. Where an obstacle was not considered, both wayfinding methods gave the same route. From the simulation results, it can be concluded that the shortest route can be determined by the familiarity of environment method where there is no obstacle.

In a real emergency evacuation, an unpredictable obstacle might appear in the building and can be a serious matter if it is blocking the evacuation route. Our simulation output for such scenario has shown that when an obstacle has cut off the straight evacuation route, some occupants who had followed their familiar route had to detour and to avoid the obstacle. This detour had consumed extra time. The simulation reports also show that some occupants were trapped at the site of the obstacle. In the simulation of hostel evacuation, 48 people who followed the normal familiar route were trapped inside the hostel. This shows that current knowledge of building layout and facilities could not provide sufficient information in deciding the safest and fastest evacuation route. Occupant of high-rise buildings need to knoe the precise and detail layout of their buildings. The precise identification of obstacle status and location can be detected by pre-installed emergency which can be used to support communication during emergency situation. The most ideal emergency system is one that able to provide updated and complete information about the real time situation in the building. A good communication is highly important during the emergency evacuation and guidance is needed to determine the safe route.

In evacuation planning where safety is the highest priority, the term shortest route is not appropriate since the term shortest route is more focused on getting the fastest evacuation time. The term feasible route is preferred instead of shortest route. A feasible route in the event of evacuation means a route that fulfills the primary objective of evacuation i.e.: hazard free (safe) and the shortest route to the assembly point. If the shortest route seems like a straightforward pattern of node in the network model, the feasible route tends to have a zigzag pattern of node.

In chapter 2, this thesis presented some previous studies that has introduced a leader as the guide in evacuation. (Pelechano, et al., 2006) has introduced a leader agent with an ability to determine the shortest route. The idea presented by (Pelechano, et al., 2006) is incorporated in our proposed emergency exit agent where the agent represents real occupant in the building and has the ability to guide other occupants and to monitor the building situation. The simulation results by (Pelechano, et al., 2006) have shown that a trained leader has a significant impact to improve evacuation process. A Leader who is able to communicate with the central emergency room would be able to updates of the situation in the building. Alternatively, a direct perception of the environmental conditions can be used to determine the safest and shortest evacuation route. The study of a leader's contribution during evacuation has strengthened the importance of feasible route determination and not only to focus on speeding up the evacuation time.

(Pelechano, et al., 2006) has concluded that the optimal number of trained leaders is 10% of the total number of building occupants. For a simple calculation, if total number of occupant is approximately 1000 people, 100 trained leaders are needed to help in the evacuation process. Hence, the safety management planning should place high priority on identifying and training some occupants in the building to become group leaders responsible for guiding other occupants to safe evacuation during an emergency crisis.

The simulation has shown the significant contribution of the modified exit sign as the smart devices in evacuation planning. The exits sign, which ACO as the main algorithm to determine the route, has the possibility to be implemented as the smart facility in an emergency system. One of the advantages of the proposed smart exit sign as compared to the human leader as a smart guide lies in the ability to communicate automatically and directly with the other emergency sensors in the building. Each occupant will be guided directly to the feasible route from any building location to the final assembly point. In addition, the proposed smart exit sign offers a better capability to locate any obstacle around the building and to identify the feasible routes.

5.6. Summary

This chapter presents an experiment to investigate the wayfinding method during evacuation process. In the beginning part, ant system as the algorithm to determine evacuation route is presented. Ant system has been expanded by adding new parameter, traffic on node ij, for probability function of ant system.

Exit sign as standard direction facility in the building has been introduced as a smart agent in the evacuation simulation. Smart exit sign where expanded ACO has embedded on it has been built with a capability to determine the evacuation route by considering any obstacle in the building. This method, ACO wayfinding, is compared with familiarity of environment wayfinding method. Both wayfinding methods show same performance to reach the evacuation process where no obstacle applied. But, the familiarity wayfinding method has taken 21.6% longer than ACO wayfinding method when an obstacle applied in the simulation.

CHAPTER SIX: CONCLUSIONS

This chapter summarizes the research findings, contributions, and compares those contributions with some previous and related works, and also suggests some other relevant areas for the future works.

6.1. Human Behavior and Evacuation Simulation

Some improvements in the evacuation planning are proposed in this thesis in order to reduce the TET. The dynamics of an evacuation process are presented in the simulation where some related human behaviors have been considered. Both the pre-evacuation phase and movement phases have been studied with some opportunities are offered in minimizing the TET.

6.1.1. Pre-Evacuation phase

TET as the main indicator to assess the performance of an evacuation process has been defined completely and clearly. Many existing evacuation simulators have used a simple RNG to generate the departing time of each occupant. However, in this work, SEEP 1.5 has been used to model human cognitive behavior in generating the pre-evacuation time. The simulation result shows that pre-evacuation phase consumed 60.4% of TET where Proulx's pre-evacuation drill results took approximately 70% of TET. The pre-evacuation phase consist of recognition time (35.4% of TET), start to egress or preparation time (21.1% of TET), and investigating path (14.5% of TET). Since no other actions were carried out to increase their safety awareness, those actions during the pre-evacuation phase can be classified as wasting activities. A sensitivity analysis has shown that the TET can be reduced to 41% just by eliminating the recognition time in pre-evacuation phase.

6.1.2. Prometheus Methodology

The dynamic movement of human interaction and communication can be studied by using the agent-based simulation. There are some associated processes between definition of Prometheus components' with simulation system descriptions, such as goals, functionalities, interaction between system entities, data sharing, and capabilities. Overall, the Prometheus steps are easy to understand and have been helpful in assisting the user to develop the evacuation simulation model. It starts by defining the general definition of an evacuation system, followed by developing the architectural design, and finally exploring the agent detailed design. Another advantage of the Prometheus methodology to this work is each hypothesis was treated as a part of the simulation scenarios where the involved goals, perceive and functionalities were be arranged as sequencing processes.

6.1.3. Wayfinding Methods

As the natural and most common wayfinding method, familiarity of environment comes with a straightforward pattern of route formed by a routine. Indeed, familiarity wayfinding method is able to determine the shortest evacuation route, where the obstacle existence is denied. However, when an obstacle appeared in the building, our simulation result has shown that it is not safe to solely depend on the routine route. In actual emergency situation, where safety must be the primary objective of evacuation, guidance for safe evacuation must be provided and the safest reliable route must be determined. Smart exit sign has been introduced in this thesis in order to present the ACO wayfinding method.

A new parameter, traffic on node, has been added to ACO probability function. The expanded ACO is able to determine the evacuation route by identifying the location and recognizing the obstacle status in the building. In the hostel simulation, the exit sign has been modified as the smart agent with the capability to determine the evacuation route and guide the occupants to reach the final assembly point. An ACO algorithm has been embedded on the emergency exit agent. In the hostel evacuation simulation, the TET of the ACO wayfinding method is 21.6% faster rather than that of familiarity wayfinding method, even in the presence of obstacles. From that comparison, it is learnt that a local based decision does not always assure the occupants take the feasible route in evacuation. For safety reasons, the term feasible route is more appropriate than the term shortest route because shortest route does not always mean the feasible route.

The main reason for developing SEEP 1.5, is to investigate specific human behavior that could potentially affects TET. SEEP 1.5 is capable in simulating not only the common evacuation process but also simulating customized scenarios. Even though SEEP 1.5 still needs more improvements, cognitive behavior model has been attached in SEEP 1.5 where pre-evacuation phase has become more realistic than other existing simulators. Pre-evacuation phase should not be simplified in a simulation because half of TET is consumed by this phases, which is caused by time wasting activity mostly. Since this thesis is focused on cognitive modeling in the pre-evacuation and also studying the wayfinding method during movement, some other human behaviors such as group behavior, kin behavior and leader contributions might be considered as a part of SEEP 1.5 improvement for better representation of real situations.

6.2. Discussion on Research Findings and Previous Works

This section presents some discussion of research's findings in relation to the previous works.

6.2.1. Pre-evacuation time

This thesis has applied the human cognitive behavior model to generate the pre-evacuation time. Using SEEP 1.5, the pre-evacuation time is in good fit with the Weibull distribution. Some occupants tend to take much longer to evacuate than the majority. This result has a similarity with the real drill conducted by Purser, et al.(2001). The spread of data based on Purser, et al., follows the log normal distribution and this skewed of data is similar with our simulation result. A graphical comparison between the pre-evacuation time generated by our simulation and pre-evacuation time generated by using RNG has shown that the spread of pre-evacuation time using the RNG's cannot be used to represent the realistic pre-evacuation time. The result from RNG failed to present the behavior of human in pre-evacuation phase.

From our research finding in chapter 4, the building management or evacuation planner must consider the pre-evacuation phase with some human behavior involved. The proportion of pre-evacuation phase has confirmed the real evacuation exercise and observation's result conducted by Proulx (1995).With the similar complexity of building evacuation, (Proulx's experiment involved 150 occupants, and SEEP 1.5 simulated 180 occupants), we provide the similar conclusion of result, that is more that half of TET has been formed during the pre-evacuation phase. This result also similar with Purser, et al (2001)'s evacuation drill, from their graphical presentations, it show that pre-evacuation time takes much longer than the movement time.

Human cognitive behavior model has been applied in SEEP 1.5 in order to simulate the dynamic of human behavior during pre-evacuation phase. Although Pires (2005) did not provide the model's result through computer simulation, he has concluded that the evacuation planner should focus on pre-evacuation phase. This thesis has applied the human cognitive model using computer simulation, and also shows that the Pires' model can be integrated with the computer simulation. Pires developed the human cognitive model with some input parameter as a probability values. Since the determination of probability value is not similar from one group of population with another, it is important to validate the probability value as the input of pre-evacuation time generation.

6.2.2. Prometheus methodology implementation

In this thesis, Prometheus methodology has been applied to develop the evacuation simulation. Since none of previous simulators present their detailed system development, a detailed approach of Prometheus for building the component of evacuation system has became the major contribution of this thesis research work.

Prometheus methodology provides a detailed design for each agent including the capability, the plan, and the procedure of each agent. From the modeling point of view, we agree that Prometheus provides a clear notation, ease to learn and use, ease to trace, ease to check the model consistency, and guide the user using the top-down approach. Although a comparison of some agent-based methodology has not been provided in this thesis, based on our evacuation system development process, Prometheus is recommended to other complex system development and system with intelligence aspect. Unfortunately, the PDT software has not been provided with the executable application to run the program.

6.2.3. Wayfinding methods

In chapter 5, ACO wayfinding method has been introduced. It provides an opportunity to improve the movement time of occupant. ACO wayfiding has been performed faster than Familiarity of Environment wayfinding to reach the assembly point. From this result, it can be recommended that smart emergency exit sign (emergency exit agent) will provide better guidance to the occupant during evacuation. This thesis did not present the direct comparison between smart emergency exit sign and leader in evacuation simulation. But since the common leader also follow their past experience and familiarity of building layout, it can be associated that leader’s decision to determine the route follow the familiarity of environment method. The direct comparison of our simulation and the previous works from Murakami, et al. (2002), Pelechano, et al. (2006), and Sugitomo (2005), is difficult to be presented since the difference of problem complexity and the availability of data.

The term “Feasible route” is introduced in this thesis where the route determination will not only achieve the shortest route but also should consider the possibly obstacle appeared in the building area. SEEP 1.5 is able to determine the feasible route. This capability is also the major contributions of this thesis to evacuation software development since less or maybe none of the existing evacuation simulations are not provided this capability. Another strength point of our thesis is the expansion of ACO is applied to determine the feasible route. Based on these research achievements, the evacuation planning can be improved significantly, especially for the study of evacuation simulation.

6.3. Thesis Contributions

Some challenging opportunities to enhance the evacuation system are introduced as part of these research contributions. There are some contributions of this thesis to be highlighted as the followings.

1. This thesis has developed an agent-based simulation in evacuation planning and has presented some human behavior into simulation, such as panic movement, pre-evacuation behavior, queuing behavior, and wayfinding behavior.
2. This thesis has provided a practical application for agent-based development in evacuation simulation using Prometheus methodology.
3. This thesis has conducted evacuation survey related to people's response during pre-evacuation phase and some exploration of people's activities during pre-evacuation phase.
4. This thesis has done some evaluations about human behavior in pre-evacuation phase by applying human cognitive model into simulation.
5. This thesis has presented a comparison of two wayfinding methods to get the shortest route in movement phase.
6. This thesis has proposed expansion of ant colony algorithm in order to determine the feasible route in movement phase.
7. This thesis has introduced dynamic exit sign as the occupant's guidance in movement phase.

6.4. Limitation of Study

There are many factors and variables that need to be considered in the simulation of human behaviors in emergency building evacuation. Some limitations of the modeling and simulation part have been identified in this work.

The sensitivity analysis result has shown that the TET can be reduced by increasing the occupants' awareness to the emergency notification. In this thesis, some discussions have been presented to analyze the pre-evacuation phase. However, further study to simulate people's response to the alarm notification has not been included. A further study to obtain other responses from the occupants through real evacuation survey is recommended since direct observations on human response are needed in order to obtain accurate information.

(Sugimoto, 2005) and (Pelechano, et al., 2006) presented the leadership behavior in group evacuation. The leadership skill has a significant contribution on the wayfinding method. On the other hand, a human leader has some limited capability to lead a group effectively in real emergency situations. A leader select the evacuation route would be based on his/her familiarity of building environment and local communication.

The SEEP 1.5 was only tested on the hostel building, which consist of 4 level of floor. However, it is known that the number of floor in a building would increase the crowd level at the ground floor. Therefore, simulations of higher floor level should be performed to observe the crowd problem with more complex evacuation process.

6.5. Future Works

For further development of introduced scenarios, a challenging future work has been stated to apply this simulator to another different extreme building such as nuclear plant, crowded stadium or higher high-rise public building. In the case of hostel evacuation, only four levels of building are being simulated. Once the complexity of building is increase, different characteristic of evacuation might be explored. Prediction of evacuation factors for higher level of building becomes the other opportunity to expand the scope of evacuation planning. Crowded level, queuing characteristic, number of safe people, number of trapped people for the higher building evacuation might be predicted by multiply the building level in the simulation.

Inspired by simulation result in pre-evacuation phase, increasing people awareness to alarm signal become the unsolved problem in safety area. Another opportunity as the future research to minimize the response is applying direct notification by centre of emergency control to each occupant in the fired building. Mobile application with mobile phone communication such as SMS alert system in evacuation planning might enhance the pre-evacuation performance.

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Publications and Awards

1. Rahman, A., and Kamil, A., "Feasible Route Determination using Ant Colony Optimization in Evacuation Planning", IEEE Scored Conference, Kuala Lumpur, 2007.
2. Rahman, A., and Kamil, A., "Developing Agent-Based Simulation in Evacuation Planning", National Postgraduate Conference, Tronoh, 2008.
3. Rahman, A., and Kamil, A., "Agent-based simulation using Prometheus Methodology in Evacuation Planning", IEEE International Symposium on Information Technology (ITSIM) Conference, Kuala Lumpur, 2008.
4. Rahman, A., and Kamil, A., "Simulating Human Cognitive Behavior in Pre-Evacuation", IEEE International Symposium on Information Technology (ITSIM) Conference, Kuala Lumpur, 2008.
5. Rahman, A., and Kamil, A., "Clearance Time Reduction in Pre-Evacuation Planning", Asia Pacific Industrial Engineering & Management Systems (APIEMS) Conference, Bali, 2008.
6. Rahman, A., and Kamil, A., "Using Agent-Based Simulation of Human Behavior to Reduce Evacuation Time", 11th Pacific Rim International Conference on Multi-Agents (PRIMA), Hanoi, 2008 (to be published in Springer Lecture Notes in Computer Science).
7. Bronze medal (Postgraduate categories) on Engineering Design Exhibition 2007.
8. 2nd Best poster (Postgraduate categories) on Engineering Design Exhibition 2007.
9. Silver medal (Postgraduate categories) on Engineering Design Exhibition 2008.

Glossary

ACO wayfinding	Evacuation route determination applies the ACO algorithm to find the feasible route.
Ant Colony Optimization	Selection algorithm based on the Ant System.
Assembly point	The save area for gathering due to evacuation process.
Clearance time	Time to perform the evacuation process, from the event of alarm ring to the event of reaching the assembly point.
Capability (in Prometheus)	a modules attached to the agents as a refinery of its functionality
Disaster	An event resulting in great loss and misfortune
Experimental design	The design of all information-gathering exercises where variation is present
Dynamic movement	Acceleration of movement
Evacuation	The act of evacuating or leaving the place to get the protection
Evacuation drill	Systematic training to simulate the evacuation process
Exit Sign	Static guidance in the building to show the evacuation route.
Familiarity of environment	Knowledge about the building structure and facility
Feasible route	A route which consider the safety and the minimum evacuation time
Functionality (in Prometheus)	A process to refine and grouping some goals in system specification
High-rise Building	A building with many occupants where maximum height of the rescue capability is not able to reach the top level of the building
Ignoring immediate leaving	Refuse the warning from the emergency notification
Investigating path	Looking for appropriate path during evacuation
Movement Phase	Evacuation period where the occupant leave their original position to the assembly point.
Multi-agent	A group of cooperative or competitive agents
Network diagram	A general type of diagram, which represents some kind of network
Occupant	Someone who lives at a particular place for a prolonged period
Panic	An overwhelming feeling of fear and anxiety
Pheromone	The medium that is used to communicate information among ants.
Pheromone trail	Trail of ant’s journey.
Physical Obstacle	A physical obstruction that stands in the evacuation

	route
Plan (in Prometheus)	A detailed procedure of events in Prometheus
Pre-Evacuation Phase	A period before movement
Prometheus Methodology	A systematic methodology to develop multi-agent system
Random Number Generator	A function to generate several numbers by following the random order determination.
Recognition phase	An evacuation phase to perceive the alarm notification.
Scenario	A synthetic description of an event or series of actions and events
Shortest route	A route which consider the minimum time or the distance
Simulation	The technique of representing the real world by a computer program
Start to Egress	A moment before leaving the building
T-test	Statistical hypothesis test in which the test statistic has a Student's *t* distribution if the null hypothesis is true
Evacuation Time	Time needed to achieve the assembly point from the event of alarm ring.
Wayfinding	The process of determining and following a route to some destination

Appendix A: Detail about Simulator for Emergency Evacuation Planning (SEEP)

In this appendix, we describe in detail the simulation components. Some important algorithms are presented in this appendix. Actually, not all the detail codes shows on this appendix and some modifications are applied to simplify the presentation. Some outputs of SEEP 1.5 can be seen in detail tables and we also provided some report of SEEP 1.5 to show detail simulation output.

A1. Some Simulation Codes and Algorithms of SEEP 1.5

ALGORITHM 7: Private Sub Maintimer_Refresh

```
Set simulation clock = ON
For a = 1 To num_people
        p = a
        If status_evacuee(a) = False Then
        PaintPicture People(p)
        loopNum(p) = loopNum(p) + 1
        ‘checking the space availability
        Call Area_definition p
        Call Space_utilization
        Call Over_space_detection
        ‘Controlling the movement
        Call Direction p, loopNum(p)
        Call Collision p
        Call Goingdown p
        Call Downstair p
        ‘reaching the assembly point
        If (pxpos(p) = assemby_point.Left And pypos(p) = assembly_point.Top Then
          num_safe_people = num_safe_people + 1
          safe_status(p) = True
          Call Evac_time_calculation p
        End If
Next a

If num_safe_people = num_people Then
  Set Simulation_clock = OFF
  Call Crowded_level_calculation
  Call Simulation_Report_Summary
  MainTimer_Refresh.Enabled = False
End if
```

ALGORITHM 8: Function Direction

```
'Turn right
If pypos(p) = node(route(p, S)).Top And pxpos(p) < node(route(p, S)).Left And next_infront(p) = 0 Then
   Peopdir(p) = 'right direction'
   pxpos(p) = pxpos(p) + running_speed(p)
ElseIf pypos(p) = node(route(p, S)).Top And pxpos(p) < node(route(p, S)).Left And next_infront(p) > 0
Then
   pxpos(p) = pxpos(p) + 0
End If

'Going down
If pxpos(p) = node(route(p, S)).Left And pypos(p) < node(route(p, S)).Top And next_infront(p) = 0 Then
   Peopdir(p) = 'down direction'
   pypos(p) = pypos(p) + running_speed(p)
ElseIf pxpos(p) = node(route(p, S)).Left And pypos(p) < node(route(p, S)).Top And next_infront(p) > 0
Then
   pypos(p) = pypos(p) + 0
End If

'Turn left
If pypos(p) = node(route(p, S)).Top And pxpos(p) > node(route(p, S)).Left And next_infront(p) = 0 Then
   Peopdir(p) = 'left direction'
   pxpos(p) = pxpos(p) - running_speed(p)
ElseIf pypos(p) = node(route(p, S)).Top And pxpos(p) > node(route(p, S)).Left And next_infront(p) > 0
Then
   pxpos(p) = pxpos(p) + 0
End If

'Going up
If pxpos(p) = node(route(p, S)).Left And pypos(p) > node(route(p, S)).Top And next_infront(p) = 0 Then
   Peopdir(p) = 'up direction'
   pypos(p) = pypos(p) - running_speed(p)
ElseIf pxpos(p) = node(route(p, S)).Left And pypos(p) > node(route(p, S)).Top And next_infront(p) > 0
Then
   pypos(p) = pypos(p) + 0
End If
End Function
```

ALGORITHM 9: Function Collision

```
position = area(p)
   For a = 1 To num_people
   If area(a) = area(p) Then
     If (a <> p) And safe_status(p) = False And safe_status(a) = False Then
        If (pxpos(p) <= pxpos(a) + 100) And (pxpos(p) >= pxpos(a) - 100) And (pypos(p) <= pypos(a) +
       100) And (pypos(p) >= pypos(a) - 100) And loopNum(a) > 0 And num_step(p) < num_step(a) Then
         Collosion (p) = true
         Recalculate running_speed(p)
      End If
     End If
   End If
```

ALGORITHM 10: Random Number Generator following Exponential and Weibull Distribution

```
If dist_type = 'Exponential' Then
      RNG = (1 - (2.7182818 ^ (-1 * dist_parameter1* (Rnd(2) * 10))))
ElseIf dist_type = 'Weibull' Then
     RNG = 1 - (2.7182818 ^ (-1 * ((Rnd(2) /  dist_parameter2) ^  dist_parameter1)))
End If
   Next a
End Function
```

A2. Simulation Outcomes

Some simulation outputs present in this sub appendix for some purposes, i.e.: simulation validation, output analysis and sensitivity analysis.

Table A.1: Walking time from simulation outputs and actual measured walking time for validation purpose

RUN	SEEP 1.5 (sec)	Actual (sec)
1	55	54
2	54	55
3	48	57
4	53	54
5	54	55
6	50	56
7	57	52
8	51	54
9	56	56
10	52	54
11	53	54.7

Summary of simulation output for sensitivity analysis are provided on below tables. In sensitivity analysis, value of leaving probability and preparing probability are modified to observe its impact to evacuation characteristics.

Table A.2: Sensitivity analysis for leaving probability ($p_{se} = 0.65$ and $p_{cp} = 0.9$)

LEAVING probability (p_{on})	**0.10**	**0.28**	**0.50**	**1.00**
CHOOSING probability (p_{cp})	**0.90**	**0.90**	**0.90**	**0.90**
PREPARING probability (p_{se})	**0.65**	**0.65**	**0.65**	**0.65**
Total Evacuation Time (sec)	401.90	335.49	253.14	192.06
crowded level	4.58%	8.89%	16.48%	21.74%

Ground floor utilization	11.31%	35.84%	58.00%	66.66%
% Time to prepare	74.40%	49.93%	28.50%	6.43%
% Time to choose	0.47%	7.20%	15.13%	31.73%
% Time to move	25.10%	42.90%	56.37%	61.50%

Table A.3: Sensitivity analysis for leaving probability (p_{se} = 0.65 and p_{cp} = 0.47)

LEAVING probability (p_{on})	**0.10**	**0.28**	**0.50**	**1.00**
CHOOSING probability (p_{cp})	**0.47**	**0.47**	**0.47**	**0.47**
PREPARING probability (p_{se})	**0.65**	**0.65**	**0.65**	**0.65**
Total Evacuation Time (sec)	408.90	296.57	248.46	201.35
crowded level	4.28%	7.27%	12.26%	18.31%
Ground floor utilization	10.46%	28.66%	49.50%	61.60%
% Time to prepare	78.30%	63.83%	48.17%	29.33%
% Time to choose	0.40%	6.20%	12.53%	19.67%
% Time to move	21.30%	29.97%	39.27%	51.00%

Table A.4: Sensitivity analysis for leaving probability (p_{se} = 0.65 and p_{cp} = 0)

LEAVING probability (p_{on})	**0.10**	**0.28**	**0.5**	**1.00**
CHOOSING probability (p_{cp})	**0.00**	**0.00**	**0.00**	**0.00**
PREPARING probability (p_{se})	**0.65**	**0.65**	**0.65**	**0.65**
Total Evacuation Time (sec)	503.70	465.08	363.06	238.25
crowded level	3.54%	4.15%	5.58%	6.09%
Ground floor utilization	8.19%	10.38%	14.18%	18.40%
% Time to prepare	82.73%	75.93%	70.43%	61.00%
% Time to choose	0.20%	0.50%	0.67%	1.77%
% Time to move	17.07%	23.60%	28.93%	37.23%

Detail route determinations for each occupant are presented on below tables. This below table shows the route determination without considering the obstacle status in the building and the route determination considering the obstacle in the building.

Table A.5: Detail route determinations for each occupant in Hostel simulation

	WITHOUT OBSTACLE		WITH OBSTACLE	
OCC. NO.	ROUTE FOLLOWING FAMILIARITY	ROUTE FOLLOWING ACO	ROUTE FOLLOWING FAMILIARITY	ROUTE FOLLOWING ACO
1	1-3-4-12-20-28-32-33	1-3-4-12-20-28-32-33	1-3-4-12-20-12-16-24-31-32-33	1-3-8-16-24-31-32-33
2	1-3-4-12-20-28-32-33	1-3-4-12-20-28-32-33	1-3-4-12-20-12-16-24-31-32-33	1-3-4-12-16-24-31-32-33
3	1-3-4-12-20-28-32-33	1-3-4-12-20-28-32-33	1-3-4-12-20-12-16-24-31-32-33	1-3-4-12-16-24-31-32-33
4	1-3-4-12-20-28-32-33	1-3-4-12-20-28-32-33	1-3-4-12-20-12-16-24-31-32-33	1-3-4-12-16-24-20-28-32-33
5	1-3-4-12-20-28-32-33	1-3-4-12-20-28-32-33	1-3-4-12-20-12-16-24-31-32-33	1-3-4-12-16-24-20-28-32-33
6	1-3-4-12-20-28-32-33	1-3-8-16-24-31-32-33	1-3-4-12-20-12-16-24-31-32-33	1-3-8-16-24-31-32-33-
7	1-3-4-12-20-28-32-33	1-3-4-12-20-28-32-33	1-3-4-12-20-12-16-24-31-32-33	1-3-4-12-16-24-20-28-32-33
8	1-3-4-12-20-28-32-33	1-3-8-16-24-31-32-33	1-3-4-12-20-12-16-24-31-32-33	1-3-8-16-24-31-32-33
9	1-3-4-12-20-28-32-33	1-3-8-16-24-31-32-33	1-3-4-12-20-12-16-24-31-32-33	1-3-8-16-24-31-32-33
10	1-3-4-12-20-28-32-33	1-3-8-16-24-31-32-33	1-3-4-12-20-12-16-24-31-32-33	1-3-8-16-24-31-32-33
11	1-3-4-12-20-28-32-33	1-3-4-12-20-28-32-33	1-3-4-12-20-12-16-24-31-32-33	1-3-4-12-16-24-20-28-32-33
12	1-3-4-12-20-28-32-33	1-3-4-12-20-28-32-33	1-3-4-12-20-12-16-24-31-32-33	1-3-4-12-16-24-31-32-33
13	5-7-8-16-24-31-32-33	5-7-8-16-24-31-32-33	5-7-8-16-24-31-32-33	5-7-8-16-24-31-32-33
14	5-7-8-16-24-31-32-33	5-7-8-16-24-31-32-33	5-7-8-16-24-31-32-33	5-7-8-16-24-31-32-33
15	5-7-8-16-24-31-32-33	5-7-8-16-24-31-32-33	5-7-8-16-24-31-32-33	5-7-8-16-24-31-32-33
16	5-7-8-16-24-31-32-33	5-7-8-16-24-31-32-33	5-7-8-16-24-31-32-33	5-7-8-16-24-31-32-33
17	5-7-8-16-24-31-32-33	5-7-8-16-24-31-32-33	5-7-8-16-24-31-32-33	5-7-8-16-24-31-32-33
18	5-7-8-16-24-31-32-33	5-7-4-12-20-28-32-33	5-7-8-16-24-31-32-33	5-7-4-12-16-24-20-28-32-33
19	5-7-8-16-24-31-32-33	5-7-8-16-24-31-32-33	5-7-8-16-24-31-32-33	5-7-8-16-24-31-32-33
20	5-7-8-16-24-31-32-33	5-7-8-16-20-28-32-33	5-7-8-16-24-31-32-33	5-7-8-16-24-31-32-33
21	5-7-8-16-24-31-32-33	5-7-8-16-24-31-32-33	5-7-8-16-24-31-32-33	5-7-8-16-24-31-32-33
22	5-7-8-16-24-31-32-33	5-7-8-16-24-31-32-33	5-7-8-16-24-31-32-33	5-7-8-16-24-31-32-33
23	5-7-8-16-24-31-32-33	5-7-4-12-20-28-32-33	5-7-8-16-24-31-32-33	5-7-4-12-16-24-20-28-32-33
24	5-7-8-16-24-31-32-33	5-7-8-16-24-31-32-33	5-7-8-16-24-31-32-33	5-7-8-16-24-31-32-33
25	2-3-4-12-20-28-32-33	2-3-4-12-20-28-32-33	2-3-4-12-20-12-16-24-31-32-33	2-3-4-12-16-24-31-32-33
26	2-3-4-12-20-28-32-33	2-3-4-12-20-28-32-33	2-3-4-12-20-12-16-24-31-32-33	2-3-4-12-16-24-20-28-32-33
27	2-3-4-12-20-28-32-33	2-3-4-12-20-28-32-33	2-3-4-12-20-12-16-24-31-32-33	2-3-4-12-16-24-31-32-33
28	2-3-4-12-20-28-32-33	2-3-4-12-16-24-31-32-33	2-3-4-12-20-12-16-24-31-32-33	2-3-4-12-16-24-31-32-33
29	2-3-4-12-20-28-32-33	2-3-4-12-20-28-32-33	2-3-4-12-20-12-16-24-31-32-33	2-3-4-12-16-24-20-28-32-33
30	2-3-4-12-20-28-32-33	2-3-4-12-20-28-32-33	2-3-4-12-20-12-16-24-31-32-33	2-3-4-12-16-24-20-28-32-33
31	2-3-4-12-20-28-32-33	2-3-8-16-24-31-32-33	2-3-4-12-20-12-16-24-31-32-33	2-3-8-16-24-31-32-33
32	2-3-4-12-20-28-32-33	2-3-8-16-24-31-32-33	2-3-4-12-20-12-16-24-31-32-33	2-3-8-16-24-31-32-33
33	2-3-4-12-20-28-32-33	2-3-4-12-20-28-32-33	2-3-4-12-20-12-16-24-31-32-33	2-3-4-12-16-24-31-32-33
34	2-3-4-12-20-28-32-33	2-3-8-16-24-31-32-33	2-3-4-12-20-12-16-24-31-32-33	2-3-8-16-24-31-32-33
35	2-3-4-12-20-28-32-33	2-3-8-16-24-31-32-33	2-3-4-12-20-12-16-24-31-32-33	2-3-8-16-24-31-32-33
36	2-3-4-12-20-28-32-33	2-3-4-12-20-28-32-33	2-3-4-12-20-12-16-24-31-32-33	2-3-4-12-16-24-20-28-32-33
37	6-7-8-16-24-31-32-33	6-7-8-16-24-31-32-33	6-7-8-16-24-31-32-33	6-7-8-16-24-31-32-33

	WITHOUT OBSTACLE		WITH OBSTACLE	
OCC. NO.	ROUTE FOLLOWING FAMILIARITY	ROUTE FOLLOWING ACO	ROUTE FOLLOWING FAMILIARITY	ROUTE FOLLOWING ACO
38	6-7-8-16-24-31-32-33	6-7-8-16-24-31-32-33	6-7-8-16-24-31-32-33	6-7-8-16-24-31-32-33
39	6-7-8-16-24-31-32-33	6-7-4-12-20-28-32-33	6-7-8-16-24-31-32-33	6-7-4-12-16-24-20-28-32-33
40	6-7-8-16-24-31-32-33	6-7-8-16-24-31-32-33	6-7-8-16-24-31-32-33	6-7-8-16-24-31-32-33
41	6-7-8-16-24-31-32-33	6-7-4-12-20-28-32-33	6-7-8-16-24-31-32-33	6-7-4-12-16-24-20-28-32-33
42	6-7-8-16-24-31-32-33	6-7-8-16-24-31-32-33	6-7-8-16-24-31-32-33	6-7-8-16-24-31-32-33
43	6-7-8-16-24-31-32-33	6-7-8-16-24-31-32-33	6-7-8-16-24-31-32-33	6-7-8-16-24-31-32-33
44	6-7-8-16-24-31-32-33	6-7-4-12-20-28-32-33	6-7-8-16-24-31-32-33	6-7-4-12-16-24-20-28-32-33
45	6-7-8-16-24-31-32-33	6-7-8-16-24-31-32-33	6-7-8-16-24-31-32-33	6-7-8-16-24-31-32-33
46	6-7-8-16-24-31-32-33	6-7-4-12-20-28-32-33	6-7-8-16-24-31-32-33	6-7-4-12-16-24-20-28-32-33
47	6-7-8-16-24-31-32-33	6-7-4-12-20-28-32-33	6-7-8-16-24-31-32-33	6-7-4-12-16-24-20-28-32-33
48	6-7-8-16-24-31-32-33	6-7-8-16-24-31-32-33	6-7-8-16-24-31-32-33	6-7-8-16-24-31-32-33
49	9-11-12-20-28-32-33	9-11-12-20-28-32-33	9-11-12-20-12-16-24-31-32-33	9-11-16-24-20-28-32-33
50	9-11-12-20-28-32-33	9-11-12-20-28-32-33	9-11-12-20-12-16-24-31-32-33	9-11-16-24-20-28-32-33
51	9-11-12-20-28-32-33	9-11-12-20-28-32-33	9-11-12-20-12-16-24-31-32-33	9-11-16-24-20-28-32-33
52	9-11-12-20-28-32-33	9-11-12-20-28-32-33	9-11-12-20-12-16-24-31-32-33	9-11-16-24-31-32-33
53	9-11-12-20-28-32-33	9-11-12-20-28-32-33	9-11-12-20-12-16-24-31-32-33	9-11-16-24-20-28-32-33
54	9-11-12-20-28-32-33	9-11-16-24-31-32-33	9-11-12-20-12-16-24-31-32-33	9-11-16-24-31-32-33
55	9-11-12-20-28-32-33	9-11-16-24-31-32-33	9-11-12-20-12-16-24-31-32-33	9-11-16-24-31-32-33
56	9-11-12-20-28-32-33	9-11-12-20-28-32-33	9-11-12-20-12-16-24-31-32-33	9-11-16-24-31-32-33
57	9-11-12-20-28-32-33	9-11-12-20-28-32-33	9-11-12-20-12-16-24-31-32-33	9-11-16-24-20-28-32-33
58	9-11-12-20-28-32-33	9-11-12-20-28-32-33	9-11-12-20-12-16-24-31-32-33	9-11-16-24-20-28-32-33
59	9-11-12-20-28-32-33	9-11-12-20-28-32-33	9-11-12-20-12-16-24-31-32-33	9-11-16-24-20-28-32-33
60	9-11-12-20-28-32-33	9-11-12-16-24-31-32-33	9-11-12-20-12-16-24-31-32-33	9-11-16-24-31-32-33
61	13-15-16-24-31-32-33	13-15-16-24-31-32-33	13-15-16-24-31-32-33	13-15-16-24-31-32-33
62	13-15-16-24-31-32-33	13-15-16-24-31-32-33	13-15-16-24-31-32-33	13-15-16-24-31-32-33
63	13-15-16-24-31-32-33	13-15-16-24-31-32-33	13-15-16-24-31-32-33	13-15-16-24-31-32-33
64	13-15-16-24-31-32-33	13-15-12-20-28-32-33	13-15-16-24-31-32-33	13-15-16-24-20-28-32-33
65	13-15-16-24-31-32-33	13-15-16-24-31-32-33	13-15-16-24-31-32-33	13-15-16-24-31-32-33
66	13-15-16-24-31-32-33	13-15-12-20-28-32-33	13-15-16-24-31-32-33	13-15-16-24-20-28-32-33
67	13-15-16-24-31-32-33	13-15-12-20-28-32-33	13-15-16-24-31-32-33	13-15-16-24-20-28-32-33
68	13-15-16-24-31-32-33	13-15-16-24-31-32-33	13-15-16-24-31-32-33	13-15-16-24-31-32-33
69	13-15-16-24-31-32-33	13-15-12-20-28-32-33	13-15-16-24-31-32-33	13-15-16-24-20-28-32-33
70	13-15-16-24-31-32-33	13-15-16-24-31-32-33	13-15-16-24-31-32-33	13-15-16-24-31-32-33
71	13-15-16-24-31-32-33	13-15-16-24-31-32-33	13-15-16-24-31-32-33	13-15-16-24-31-32-33
72	13-15-16-24-31-32-33	13-15-12-20-28-32-33	13-15-16-24-31-32-33	13-15-16-24-20-28-32-33
73	10-11-12-20-28-32-33	10-11-16-24-31-32-33	10-11-12-20-12-16-24-31-32-33	10-11-16-24-31-32-33
74	10-11-12-20-28-32-33	10-11-12-20-28-32-33	10-11-12-20-12-16-24-31-32-33	10-11-16-24-31-32-33
75	10-11-12-20-28-32-33	10-11-12-20-28-32-33	10-11-12-20-12-16-24-31-32-33	10-11-16-24-20-28-32-33

	WITHOUT OBSTACLE		WITH OBSTACLE	
OCC. NO.	ROUTE FOLLOWING FAMILIARITY	ROUTE FOLLOWING ACO	ROUTE FOLLOWING FAMILIARITY	ROUTE FOLLOWING ACO
76	10-11-12-20-28-32-33	10-11-16-24-31-32-33	10-11-12-20-12-16-24-31-32-33	10-11-16-24-31-32-33
77	10-11-12-20-28-32-33	10-11-12-16-24-31-32-33	10-11-12-20-12-16-24-31-32-33	10-11-16-24-31-32-33
78	10-11-12-20-28-32-33	10-11-12-20-28-32-33	10-11-12-20-12-16-24-31-32-33	10-11-16-24-31-32-33
79	10-11-12-20-28-32-33	10-11-12-20-28-32-33	10-11-12-20-12-16-24-31-32-33	10-11-16-24-31-32-33
80	10-11-12-20-28-32-33	10-11-12-20-28-32-33	10-11-12-20-12-16-24-31-32-33	10-11-16-24-20-28-32-33
81	10-11-12-20-28-32-33	10-11-12-20-28-32-33	10-11-12-20-12-16-24-31-32-33	10-11-16-24-31-32-33
82	10-11-12-20-28-32-33	10-11-12-16-24-31-32-33	10-11-12-20-12-16-24-31-32-33	10-11-16-24-31-32-33
83	10-11-12-20-28-32-33	10-11-16-24-31-32-33	10-11-12-20-12-16-24-31-32-33	10-11-16-24-31-32-33
84	10-11-12-20-28-32-33	10-11-16-24-31-32-33	10-11-12-20-12-16-24-31-32-33	10-11-16-24-31-32-33
85	14-15-16-24-31-32-33	14-15-12-20-28-32-33	14-15-16-24-31-32-33	14-15-16-24-20-28-32-33
86	14-15-16-24-31-32-33	14-15-16-24-31-32-33	14-15-16-24-31-32-33	14-15-16-24-31-32-33
87	14-15-16-24-31-32-33	14-15-16-24-31-32-33	14-15-16-24-31-32-33	14-15-16-24-31-32-33
88	14-15-16-24-31-32-33	14-15-16-24-31-32-33	14-15-16-24-31-32-33	14-15-16-24-31-32-33
89	14-15-16-24-31-32-33	14-15-16-24-31-32-33	14-15-16-24-31-32-33	14-15-16-24-31-32-33
90	14-15-16-24-31-32-33	14-15-16-24-31-32-33	14-15-16-24-31-32-33	14-15-16-24-31-32-33
91	14-15-16-24-31-32-33	14-15-16-24-31-32-33	14-15-16-24-31-32-33	14-15-16-24-31-32-33
92	14-15-16-24-31-32-33	14-15-16-24-31-32-33	14-15-16-24-31-32-33	14-15-16-24-31-32-33
93	14-15-16-24-31-32-33	14-15-12-20-28-32-33	14-15-16-24-31-32-33	14-15-16-24-31-32-33
94	14-15-16-24-31-32-33	14-15-16-24-31-32-33	14-15-16-24-31-32-33	14-15-16-24-31-32-33
95	14-15-16-24-31-32-33	14-15-12-20-28-32-33	14-15-16-24-31-32-33	14-15-16-24-20-28-32-33
96	14-15-16-24-31-32-33	14-15-12-20-28-32-33	14-15-16-24-31-32-33	14-15-16-24-20-28-32-33
97	17-19-20-28-32-33	17-19-20-28-32-33	17-19-20-28-32-33	17-19-20-28-32-33
98	17-19-20-28-32-33	17-19-24-31-32-33	17-19-20-28-32-33	17-19-24-31-32-33
99	17-19-20-28-32-33	17-19-20-28-32-33	17-19-20-28-32-33	17-19-20-28-32-33
100	17-19-20-28-32-33	17-19-20-28-32-33	17-19-20-28-32-33	17-19-20-28-32-33
101	17-19-20-28-32-33	17-19-20-28-32-33	17-19-20-28-32-33	17-19-20-28-32-33
102	17-19-20-28-32-33	17-19-20-28-32-33	17-19-20-28-32-33	17-19-20-28-32-33
103	17-19-20-28-32-33	17-19-20-28-32-33	17-19-20-28-32-33	17-19-20-28-32-33
104	17-19-20-28-32-33	17-19-20-28-32-33	17-19-20-28-32-33	17-19-20-28-32-33
105	17-19-20-28-32-33	17-19-20-28-32-33	17-19-20-28-32-33	17-19-20-28-32-33
106	17-19-20-28-32-33	17-19-20-28-32-33	17-19-20-28-32-33	17-19-20-28-32-33
107	17-19-20-28-32-33	17-19-20-28-32-33	17-19-20-28-32-33	17-19-20-28-32-33
108	17-19-20-28-32-33	17-19-20-28-32-33	17-19-20-28-32-33	17-19-20-28-32-33
109	21-23-24-31-32-33	21-23-24-31-32-33	21-23-24-31-32-33	21-23-24-31-32-33
110	21-23-24-31-32-33	21-23-24-31-32-33	21-23-24-31-32-33	21-23-24-31-32-33
111	21-23-24-31-32-33	21-23-24-31-32-33	21-23-24-31-32-33	21-23-24-31-32-33
112	21-23-24-31-32-33	21-23-24-31-32-33	21-23-24-31-32-33	21-23-24-31-32-33
113	21-23-24-31-32-33	21-23-20-28-32-33	21-23-24-31-32-33	21-23-20-28-32-33

	WITHOUT OBSTACLE		WITH OBSTACLE	
OCC. NO.	ROUTE FOLLOWING FAMILIARITY	ROUTE FOLLOWING ACO	ROUTE FOLLOWING FAMILIARITY	ROUTE FOLLOWING ACO
114	21-23-24-31-32-33	21-23-24-31-32-33	21-23-24-31-32-33	21-23-24-31-32-33
115	21-23-24-31-32-33	21-23-24-31-32-33	21-23-24-31-32-33	21-23-24-31-32-33
116	21-23-24-31-32-33	21-23-24-31-32-33	21-23-24-31-32-33	21-23-24-31-32-33
117	21-23-24-31-32-33	21-23-24-31-32-33	21-23-24-31-32-33	21-23-24-31-32-33
118	21-23-24-31-32-33	21-23-24-31-32-33	21-23-24-31-32-33	21-23-24-31-32-33
119	21-23-24-31-32-33	21-23-20-28-32-33	21-23-24-31-32-33	21-23-20-28-32-33
120	21-23-24-31-32-33	21-23-20-28-32-33	21-23-24-31-32-33	21-23-20-28-32-33
121	18-19-20-28-32-33	18-19-20-28-32-33	18-19-20-28-32-33	18-19-20-28-32-33
122	18-19-20-28-32-33	18-19-20-28-32-33	18-19-20-28-32-33	18-19-20-28-32-33
123	18-19-20-28-32-33	18-19-20-28-32-33	18-19-20-28-32-33	18-19-20-28-32-33
124	18-19-20-28-32-33	18-19-20-28-32-33	18-19-20-28-32-33	18-19-20-28-32-33
125	18-19-20-28-32-33	18-19-20-28-32-33	18-19-20-28-32-33	18-19-20-28-32-33
126	18-19-20-28-32-33	18-19-20-28-32-33	18-19-20-28-32-33	18-19-20-28-32-33
127	18-19-20-28-32-33	18-19-20-24-31-32-33	18-19-20-28-32-33	18-19-20-24-31-32-33
128	18-19-20-28-32-33	18-19-20-28-32-33	18-19-20-28-32-33	18-19-20-28-32-33
129	18-19-20-28-32-33	18-19-24-31-32-33	18-19-20-28-32-33	18-19-24-31-32-33
130	18-19-20-28-32-33	18-19-20-28-32-33	18-19-20-28-32-33	18-19-20-28-32-33
131	18-19-20-28-32-33	18-19-20-28-32-33	18-19-20-28-32-33	18-19-20-28-32-33
132	18-19-20-28-32-33	18-19-20-24-31-32-33	18-19-20-28-32-33	18-19-20-24-31-32-33
133	22-23-24-31-32-33	22-23-24-31-32-33	22-23-24-31-32-33	22-23-24-31-32-33
134	22-23-24-31-32-33	22-23-24-31-32-33	22-23-24-31-32-33	22-23-24-31-32-33
135	22-23-24-31-32-33	22-23-20-28-32-33	22-23-24-31-32-33	22-23-20-28-32-33
136	22-23-24-31-32-33	22-23-24-31-32-33	22-23-24-31-32-33	22-23-24-31-32-33
137	22-23-24-31-32-33	22-23-24-31-32-33	22-23-24-31-32-33	22-23-24-31-32-33
138	22-23-24-31-32-33	22-23-24-31-32-33	22-23-24-31-32-33	22-23-24-31-32-33
139	22-23-24-31-32-33	22-23-20-28-32-33	22-23-24-31-32-33	22-23-20-28-32-33
140	22-23-24-31-32-33	22-23-24-31-32-33	22-23-24-31-32-33	22-23-24-31-32-33
141	22-23-24-31-32-33	22-23-24-31-32-33	22-23-24-31-32-33	22-23-24-31-32-33
142	22-23-24-31-32-33	22-23-24-31-32-33	22-23-24-31-32-33	22-23-24-31-32-33
143	22-23-24-31-32-33	22-23-24-31-32-33	22-23-24-31-32-33	22-23-24-31-32-33
144	22-23-24-31-32-33	22-23-20-28-32-33	22-23-24-31-32-33	22-23-20-28-32-33
145	25-27-28-32-33	25-27-28-32-33	25-27-28-32-33	25-27-28-32-33
146	25-27-28-32-33	25-27-28-32-33	25-27-28-32-33	25-27-28-32-33
147	25-27-28-32-33	25-27-28-32-33	25-27-28-32-33	25-27-28-32-33
148	25-27-28-32-33	25-27-28-32-33	25-27-28-32-33	25-27-28-32-33
149	25-27-28-32-33	25-27-28-32-33	25-27-28-32-33	25-27-28-32-33
150	25-27-28-32-33	25-27-28-32-33	25-27-28-32-33	25-27-28-32-33
151	25-27-28-32-33	25-27-28-32-33	25-27-28-32-33	25-27-28-32-33

	WITHOUT OBSTACLE		WITH OBSTACLE	
OCC. NO.	ROUTE FOLLOWING FAMILIARITY	ROUTE FOLLOWING ACO	ROUTE FOLLOWING FAMILIARITY	ROUTE FOLLOWING ACO
152	25-27-28-32-33	25-27-28-32-33	25-27-28-32-33	25-27-28-32-33
153	25-27-28-32-33	25-27-28-32-33	25-27-28-32-33	25-27-28-32-33
154	25-27-28-32-33	25-27-28-32-33	25-27-28-32-33	25-27-28-32-33
155	25-27-28-32-33	25-27-28-32-33	25-27-28-32-33	25-27-28-32-33
156	25-27-28-32-33	25-27-28-32-33	25-27-28-32-33	25-27-28-32-33
157	29-30-31-32-33	29-30-31-32-33	29-30-31-32-33	29-30-31-32-33
158	29-30-31-32-33	29-30-31-32-33	29-30-31-32-33	29-30-31-32-33
159	29-30-31-32-33	29-30-31-32-33	29-30-31-32-33	29-30-31-32-33
160	29-30-31-32-33	29-30-31-32-33	29-30-31-32-33	29-30-31-32-33
161	29-30-31-32-33	29-30-31-32-33	29-30-31-32-33	29-30-31-32-33
162	29-30-31-32-33	29-30-31-32-33	29-30-31-32-33	29-30-31-32-33
163	29-30-31-32-33	29-30-31-32-33	29-30-31-32-33	29-30-31-32-33
164	29-30-31-32-33	29-30-31-32-33	29-30-31-32-33	29-30-31-32-33
165	29-30-31-32-33	29-30-31-32-33	29-30-31-32-33	29-30-31-32-33
166	29-30-31-32-33	29-30-31-32-33	29-30-31-32-33	29-30-31-32-33
167	29-30-31-32-33	29-30-31-32-33	29-30-31-32-33	29-30-31-32-33
168	29-30-31-32-33	29-30-31-32-33	29-30-31-32-33	29-30-31-32-33
169	26-27-28-32-33	26-27-28-32-33	26-27-28-32-33	26-27-28-32-33
170	26-27-28-32-33	26-27-28-32-33	26-27-28-32-33	26-27-28-32-33
171	26-27-28-32-33	26-27-28-32-33	26-27-28-32-33	26-27-28-32-33
172	26-27-28-32-33	26-27-28-32-33	26-27-28-32-33	26-27-28-32-33
173	26-27-28-32-33	26-27-28-32-33	26-27-28-32-33	26-27-28-32-33
174	26-27-28-32-33	26-27-28-32-33	26-27-28-32-33	26-27-28-32-33
175	26-27-28-32-33	26-27-28-32-33	26-27-28-32-33	26-27-28-32-33
176	26-27-28-32-33	26-27-28-32-33	26-27-28-32-33	26-27-28-32-33
177	26-27-28-32-33	26-27-28-32-33	26-27-28-32-33	26-27-28-32-33
178	26-27-28-32-33	26-27-28-32-33	26-27-28-32-33	26-27-28-32-33
179	26-27-28-32-33	26-27-28-32-33	26-27-28-32-33	26-27-28-32-33
180	26-27-28-32-33	26-27-28-32-33	26-27-28-32-33	26-27-28-32-33

A3. Simulation Reports

Report is an important component from a simulation and SEEP 1.5 has provides complete information related to appropriate simulation scenario. SEEP 1.5 creates a report a text file format or .txt.

**** SUMMARY of Simulator for Emergency Evacuation (SEEP 1.5) ****
03:43 AM, Monday, May 12, 2008

GENERAL REPORT

Number of safe occupants	=	180	
Total Simulation Clock	=	219.28	seconds
Minimum Evacuation Time	=	48.8	seconds
Maximum Pre-evacuation Time	=	177.975	seconds
Minimum Pre-evacuation Time	=	0.55	seconds
Number of trapped people on Obstacle area	=	0	

PROPORTION OF PRE-EVACUATION TIME

% Decide to leave	=	38.1 %
% Preparing the valuable items	=	33.3 %
% Choosing the evacuation route	=	28.5 %

UTILIZATION OF BUILDING FACILITIES IN EVACUATION

CROWDED LEVEL	=	17.84 %
Utilization of Hall level No. 3	=	5.28 %
Utilization of Hall level No. 2	=	14.26 %
Utilization of Hall level No. 1	=	15.44 %
Utilization of Hall level Ground	=	57.21 %
Utilization of Staircase level 3 to level 2 (Right side)	=	5.16 %
Utilization of Staircase level 3 to level 2 (Left side)	=	4.23 %
Utilization of Staircase level 2 to level 1 (Right side)	=	23.70 %
Utilization of Staircase level 2 to level 1 (Left side)	=	0.00 %
Utilization of Staircase level 1 to level G (Right side)	=	38.68 %
Utilization of Staircase level 1 to level G (Left side)	=	13.55 %

PROPORTION OF EVACUATION TIME

% Time to Prepare	=	42.7	%
% Time to Queue	=	10.4	%
% Time to Move	=	46.9	%

DETAIL REPORT (Per each occupant)

TIME TO START (Pre-Evacuation Time)

Time start Occupant no:	1	=	0.55	seconds
Time start Occupant no:	2	=	90.53	seconds
Time start Occupant no:	3	=	86.20	seconds
Time start Occupant no:	4	=	64.50	seconds
Time start Occupant no:	5	=	47.18	seconds
Time start Occupant no:	6	=	152.18	seconds
Time start Occupant no:	7	=	34.25	seconds
Time start Occupant no:	8	=	161.23	seconds
Time start Occupant no:	9	=	34.40	seconds
Time start Occupant no:	10	=	139.23	seconds
.				
.				
.				
Time start Occupant no:	171	=	72.18	seconds
Time start Occupant no:	172	=	63.63	seconds
Time start Occupant no:	173	=	37.63	seconds

Time start Occupant no: 174 = 59.45 seconds
Time start Occupant no: 175 = 151.33 seconds
Time start Occupant no: 176 = 72.58 seconds
Time start Occupant no: 177 = 125.15 seconds
Time start Occupant no: 178 = 55.38 seconds
Time start Occupant no: 179 = 68.38 seconds
Time start Occupant no: 180 = 116.60 seconds

TOTAL EVACUATION TIME (TET)

Occupant no: 1 = 64.45 seconds
Occupant no: 2 = 164.00 seconds
Occupant no: 3 = 154.45 seconds
Occupant no: 4 = 140.00 seconds
Occupant no: 5 = 117.73 seconds
Occupant no: 6 = 207.70 seconds
Occupant no: 7 = 102.45 seconds
Occupant no: 8 = 212.85 seconds
Occupant no: 9 = 96.95 seconds
Occupant no: 10 = 198.28 seconds
.
.
.
Occupant no: 171 = 183.58 seconds
Occupant no: 172 = 174.60 seconds
Occupant no: 173 = 70.08 seconds
Occupant no: 174 = 91.10 seconds
Occupant no: 175 = 205.65 seconds
Occupant no: 176 = 199.03 seconds
Occupant no: 177 = 210.98 seconds
Occupant no: 178 = 81.35 seconds
Occupant no: 179 = 213.08 seconds
Occupant no: 180 = 213.53 seconds

QUEUEING TIME

Occupant no: 1 = 0.00 seconds
Occupant no: 2 = 3.43 seconds
Occupant no: 3 = 0.68 seconds
Occupant no: 4 = 0.45 seconds
Occupant no: 5 = 0.00 seconds
Occupant no: 6 = 1.30 seconds
Occupant no: 7 = 0.00 seconds
Occupant no: 8 = 0.70 seconds
Occupant no: 9 = 1.50 seconds
Occupant no: 10 = 1.75 seconds
.
.
Occupant no: 171 = 44.53seconds
Occupant no: 172 = 43.50seconds
Occupant no: 173 = 4.05 seconds
Occupant no: 174 = 3.63 seconds
Occupant no: 175 = 19.98seconds
Occupant no: 176 = 55.75seconds
Occupant no: 177 = 39.95seconds
Occupant no: 178 = 1.45 seconds
Occupant no: 179 = 73.03seconds

Occupant no: 180 = 47.53 seconds

PRE-EVACUATION TIME

Pre-evacuation Time for each people (in seconds)

occupant no:	1	=	13.53	27.03	4.53
occupant no:	2	=	54.05	27.05	9.05
occupant no:	3	=	63.08	13.58	9.08
occupant no:	4	=	22.60	40.60	0.10
occupant no:	5	=	22.63	0.13	22.63
occupant no:	6	=	67.65	81.15	4.65
occupant no:	7	=	18.18	0.18	13.68
occupant no:	8	=	22.70	108.20	31.70
occupant no:	9	=	27.23	0.23	4.73
occupant no:	10	=	63.25	0.25	76.75
.					
.					
.					
occupant no:	171	=	13.28	8.78	49.28
occupant no:	172	=	8.80	4.30	49.30
occupant no:	173	=	13.33	4.33	17.83
occupant no:	174	=	8.85	8.85	40.35
occupant no:	175	=	17.88	116.88	17.88
occupant no:	176	=	35.90	4.40	31.40
occupant no:	177	=	49.43	67.43	8.93
occupant no:	178	=	31.45	13.45	8.95
occupant no:	179	=	17.98	31.48	17.98
occupant no:	180	=	22.50	4.50	90.00

Appendix B: Detail Validation Data (EVACNET)

In this appendix, some complement information about input definition and detail outputs for EVACNET simulation are provided in tables and report.

B1. EVANET Simulation Setup

Building dimension and hostel capacity calculation is provided on below table. Capacity's calculation and some defined variables follow EVACNET definition as provided on software guidelines (Kisko, 1999).

Table B.1: Room dimensions and capacities calculation for Hostel ground floor

Room	EVACNET code	Dimension (m)	Dimension (ft)	Area (square m)	Area (square ft)	APAO	NC	IC
Bed room	WP	3 x 3	118.11 x 118.11	9	13,949.97	2	**4**	**2**
Inside Corridor	HA	1.5 x 10	59.05 x 393.70	15	23,247.99	1.5	**10**	**0**
Outside Corridor	HA	1.5 x 10	59.05 x 393.70	15	23,247.99	1.5	**10**	**0**
Hall	LA	6 x 17	236.22 x 669.29	102	158,099.68	1.5	**68**	**0**
Staircase	SW	2x7	78.74 x 275.59	14	21,699.96	2	**7**	**0**
Corridor to Assembl y	HA	4 x 10	157.48 x 393.70	40	61,999.88	1.5	**27**	**0**

Note:
APAO = Average Pedestrian Area Occupancy (sq. ft/person)
NC = Node Capacity (people)
IC = Initial Content (people)

EVACNET need some variables to run the simulation, such as node and precedence network definition. Distance, walking speed and transfer time (capacity) should be defined in simulation setup. Node and arcs definition are provided on table B.2.

Table B.2: Node and arc definition for Hostel ground floor

FROM - TO	AFV (people/ft.min)	WR (in)	DC (people/time periods)	Distance **(DIST)**	Average Speed **(AS)**	Transfer Time **(TT)**
WP1.1 - HA1.1	13	39.37	**4**	19.69	**240**	**1**
WP2.1 - HA1.1	13	39.37	**4**	59.06	**240**	**3**
WP3.1 - HA1.1	13	39.37	**4**	118.11	**240**	**6**
WP4.1 - HA1.1	13	39.37	**4**	177.17	**240**	**9**
WP5.1 - HA1.1	13	39.37	**4**	177.17	**240**	**9**
WP6.1 - HA1.1	13	39.37	**4**	118.11	**240**	**6**
HA1.1 - HA4.1	15	59.05	**6**	59.06	**240**	**3**
WP7.1 - HA2.1	13	39.37	**4**	118.11	**240**	**6**
WP8.1 - HA2.1	13	39.37	**4**	177.17	**240**	**9**
WP9.1 - HA2.1	13	39.37	**4**	177.17	**240**	**9**
WP10.1 - HA2.1	13	39.37	**4**	118.11	**240**	**6**
WP11.1 - HA2.1	13	39.37	**4**	59.06	**240**	**3**
WP12.1 - HA2.1	13	39.37	**4**	19.69	**240**	**1**
HA2.1 - HA4.1	15	59.05	**6**	59.06	**240**	**3**
HA4.1 - LO1.1	15	59.05	**6**	19.69	**110**	**2**
WP13.1 - HA3.1	13	39.37	**4**	19.69	**240**	**1**
WP14.1 - HA3.1	13	39.37	**4**	59.06	**240**	**3**
WP15.1 - HA3.1	13	39.37	**4**	118.11	**240**	**6**
WP16.1 - HA3.1	13	39.37	**4**	177.17	**240**	**9**
WP17.1 - HA3.1	13	39.37	**4**	177.17	**240**	**9**
WP18.1 - HA3.1	13	39.37	**4**	118.11	**240**	**6**
HA3.1 - HA5.1	15	59.05	**6**	59.06	**240**	**3**
HA5.1 - LO1.1	15	59.05	**6**	19.69	**215**	**1**
LO1.1 - HA6.1	15	157.48	**16**	19.69	**110**	**2**
HA6.1 - DS1.1	15	157.48	**16**	78.74	**300**	**3**

Note:
AFV = Average Flow Volume (people/ft-min)
WR = Width Restriction - Minimal Width (in)
DC = Average Flow Volume (people/ft-min)

Simulation outputs from SEEP 1.5 and EVACNET in purposing the validation process are provided on table B.3. For validation process, 20 groups of data are presented. Unfortunately, on this validation process EVACNET has provided no variation on result for identical simulation setup.

Table B. 3: Simulation outputs of SEEP 1.5 and EVACNET for validation purpose

RUN	SEEP 1.5	EVACNET	RUN	SEEP 1.5	EVACNET
1	106.5	105	11	104.23	105
2	100.7	105	12	103.93	105
3	105.4	105	13	107.03	105
4	106.38	105	14	97.63	105
5	100.1	105	15	96	105
6	110.5	105	16	106.05	105
7	99.75	105	17	103.05	105
8	100.08	105	18	96.03	105
9	109.63	105	19	108.08	105
10	105.03	105	20	104.08	105

B2. EVACNET Simulation Report

Here are some parts of EVACNET simulation reports presented as below:

EVACNET OUTPUT for model 'Hostel Evacuation'

A. Summary of results for model id 'hostel evacuation'

21	TIME PERIODS TO EVACUATE BUILDING (105 SECONDS)
20	TIME PERIODS FOR UNCONGESTED BUILDING EVACUATION (100 SECONDS)
1.0	CONGESTION FACTOR (RATIO OF BUILDING EVACUATION TIME TO UNCONGESTED BUILDING EVACUATION TIME)
16.4	AVERAGE # OF PERIODS FOR AN EVACUEE TO EVACUATE (82 SECONDS)
1.7	AVERAGE NUMBER OF EVACUEES PER TIME PERIOD
36	NUMBER OF SUCCESSFUL EVACUEES
60	MAXIMUM # OF TIME PERIODS ALLOWED FOR EVACUATION (300 SECONDS)
39	UNNECESSARY TIME PERIODS (195 SECONDS)

B. Building evacuation profile: number of evacuees by time period for model id 'hostel evacuation'

TIME PERIOD	# OF EVACUEES	
1	0	
2	0	
3	0	
4	0	
5	0	
6	0	
7	0	
8	0	
9	0	
10	0	
11	2	**
12	4	****
13	2	**
14	4	****
15	0	
16	4	****
17	7	*******
18	1	*

19	4	****
20	7	*******
21	1	*

*Note: each * represents 1 person(s)*

C. Bottlenecks: identification of bottleneck arcs for model id 'hostel evacuation'

ARC SPECIFICATION	# OF TIME PERIODS ARC IS A BOTTLENECK	TOTAL BOTTLENECK MAGNITUDE
HA04.001-LO01.001	2	2

D. Node clearing time: time to clear a node by node for model id 'hostel evacuation'

NODE	TIME PERIOD LAST EVACUEE LEFT NODE	
HA01.001	9	(45 SECONDS)
HA02.001	10	(50 SECONDS)
HA03.001	9	(45 SECONDS)
HA04.001	13	(65 SECONDS)
HA05.001	12	(60 SECONDS)
HA06.001	18	(90 SECONDS)
LO01.001	16	(80 SECONDS)
ALL WP	0	(0 SECONDS)

NOTE: 1 TIME PERIOD = 5 SECONDS
NOTE: NODE CLEARING TIME DOES NOT INCLUDE TRANSIT TIME OF ARCS LEAVING NODE

Appendix C: ACO Comparisons for Shortest Path Problem

Shortest path problem can be defined as finding a path between two vertices where the sum of each edge's weight is minimized. Formally, what one tends to think of the 'length' of an edge is known as weight. Vertices can be a location in map, edge represents segments of road in map, and time or length of road can be defined as the weight. The term weight can be represent length, time, cost, etc, generally quantity which is to be kept minimal when going from any vertex to another.

Formally, given a weighted graph (that is, a set V of vertices, a set E of edges, and a real-valued weight function $f : E \rightarrow \mathbf{R}$), and one element v of V, find a path P from v to each v' of V so that

$$\sum_{p \in P} f(p) \qquad \text{……………………………………………………………..(C1.1)}$$

is minimal among all paths connecting v to v' .

On this appendix, some comparisons between ACO and other route determination or optimization methods are provided. It is important to know the comparison between ACO and the other heuristics algorithm to know the state of the art of shortest route methodology. Refers from (Dorigo, et al., 1997), they have provided the comparison between ACO with other heuristic algorithm in traveler salesmen problem (TSP). The TSP is a popular path optimization problem described as: "*Given a set of n vertices and weights for each pair of vertices, find a roundtrip of minimal total weight visiting each vertex exactly once*" (Taha, 2003). Table C.1 presents the comparison of ACO with GA, EP, and SA. ACO has performed excellently for some different problems. With 100-cities problem, ACO enables to get the optimum result efficiently than GA and other optimization methods.

Table C.1: Comparison between ACO with the other optimization methods

Problem Name	**Comparison Parameter**	**ACO**	**GA**	**EP**	**SA**
Oliver30	Shortest distance	**420**	421	**420**	424
(30-city problem)	Number of tours	830	3200	40000	24617
	ACS's Tour Eff. Vs. Other Method		**3**	**47**	**29**
Eil50	Shortest distance	**425**	428	426	443
(50-city problem)	Number of tours	1830	25000	100000	68512
	ACS's Tour Eff. Vs. Other Method		**13**	**54**	**36**
Eil75	Shortest distance	**535**	545	542	580
(75-city problem)	Number of tours	3480	80000	325000	173250
	ACS's Tour Eff. Vs. Other Method		**22.0**	**92.4**	**48.8**
KroA100	Shortest distance	**21282**	21761	N/A	N/A
(100-city problem)	Number of tours	4820	103000	N/A	N/A
	ACS's Tour Eff. Vs. Other Method		**20**		

Another comparison between ACO, GA, and SA is provided in figure C.1. This comparison is done by using visual boot provided by (Waite, 2006). These three different methods has performed well and showed no different result for 16 cities or small number of nodes. For 44 cities problem, ACO performed shorter tour of length to travel all the nodes. ACO has showed significant achievement when big number of cities problem applied. For 91 cities traveling problem, ACO has got shorter tour of length (581 tours) compared with GA (709) and SA (916 tours).

ACO has also been compared with Dijktra's algorithm as one of the familiar shortest path methods. Table C.2 presents that comparison which is provided by (Jiang, et al., 2007). Even Dijkstra's give minimum length of tour for some testing problems and ACO obtain the near optimum solution, ACO is more confidence to get minimum processing time for complex problems. ACO has getting efficient calculation process but less accurate in determining the optimum solution.

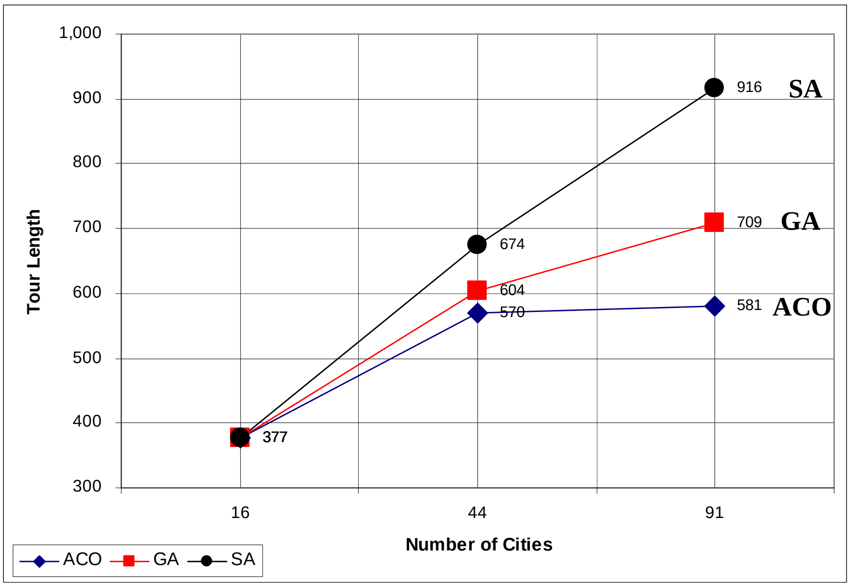

Figure C.1: Graphical Comparison of ACO with GA and SA

Table C.2: Comparison between ACO and Dijkstra's

PROBLEMS	**ACO**		**Dijkstra's**	
No of nodes	Best	Time (s)	Best	Time (s_)
400	118	0.117	118	0.056
900	183	0.225	182	0.453
2500	290	0.452	290	11.984
6400	478	0.931	464	216.360
10000	596	2.061	165	811.063

In this thesis, we also provide the comparison between ACO and Dijkstra's for 62 nodes problem. The problem is designed with width branches of node where the optimal solution can not be determined just by local searching or local weight comparison. The network presentation is depicted in figure C.2.

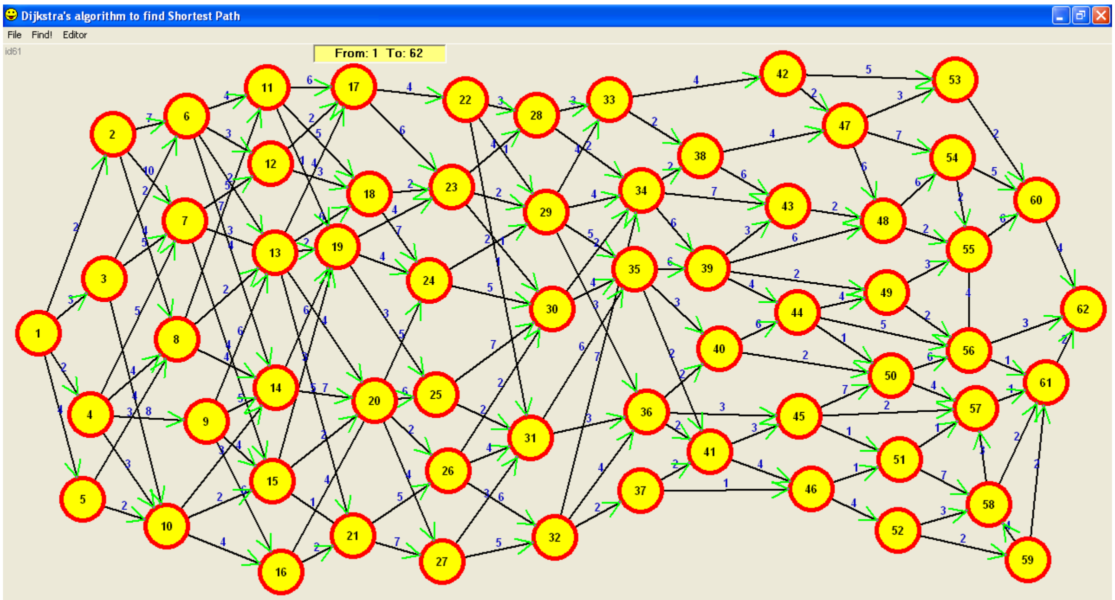

Figure C.2: Network diagram for shortest path problem

Original ant colony algorithm has been expanded to perform the shortest route problem, namely as Shortest Path Ant Colony Optimization (SPEACO) (Jiang, et al., 2007). Figure C.3 presents the SPEACO flow process.

For 62 nodes shortest path problem as seen in figure C.2, SPEACO perform fast to solve that problem. The route determine by SPEACO is **1-4-9-15-21-26-32-37-46-52-58-57-55-56-61-62** and the total travelling distance is 27. Dijkstra's algorithm able to give the shortest route, the total travelling distance performed by Dijkstra's is 26. The route taken by Dijkstra's is **1-3-6-13-19-25-31-36-45-57-61-62**.

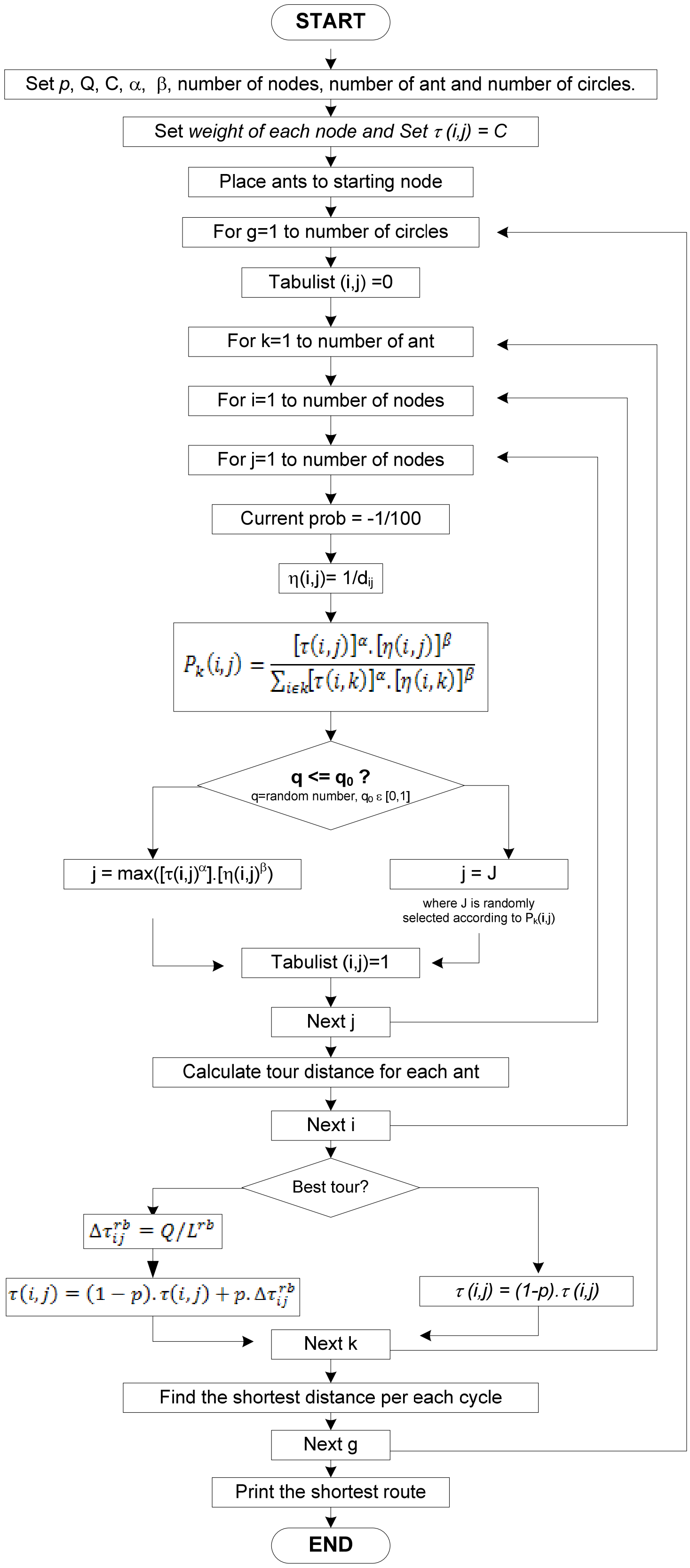

Figure C.3: Shortest Path Ant Colony Optimization (SPEACO)